



**NAVAL
POSTGRADUATE
SCHOOL**

MONTEREY, CALIFORNIA

THESIS

NPS-SCAT CONOPS AND RADIATION ENVIRONMENT

by

Adam L. Hill

June 2012

Thesis Advisor:

James H. Newman

Second Reader:

Daniel J. Sakoda

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

| | | | |
|--|---|--|--|
| REPORT DOCUMENTATION PAGE | | Form Approved OMB No. 0704-0188 | |
| Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503. | | | |
| 1. AGENCY USE ONLY (Leave blank) | | 2. REPORT DATE June 2012 | 3. REPORT TYPE AND DATES COVERED Master's Thesis |
| 4. TITLE AND SUBTITLE NPS-SCAT CONOPS and Radiation Environment | | 5. FUNDING NUMBERS | |
| 6. AUTHOR(S) Hill, Adam, L. | | 8. PERFORMING ORGANIZATION REPORT NUMBER | |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000 | | 10. SPONSORING/MONITORING AGENCY REPORT NUMBER | |
| 9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A | | 11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number N/A. | |
| 12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited | | 12b. DISTRIBUTION CODE | |
| 13. ABSTRACT (maximum 200 words) Solar cells are the primary energy-collection agents used onboard spacecraft converting energy from the sun into electricity. With solar cells being the main source of power for satellites, it is important to know how they operate and degrade when exposed to the harsh environment of low earth orbit. The objective of this thesis is to estimate the solar cell degradation that will be experienced on orbit due to radiation. This linked with the mission of the NPS-SCAT providing a quantitative measurement on orbit of how solar cells degrade over time can reduce risk of expensive national satellite by providing real-life solar cells exposure to threats of the space environment. A secondary goal of this thesis is to build and present a representation of the CONOPS (concept of operations) that describes the functionality expected on orbit. Coordination with the software programmers as well as the staff to set robust functionality is the goal for the CONOPS. This software package will be programmed into the two 1U flight certified CubeSats as their standard programming once implementation and testing have been completed. | | | |
| 14. SUBJECT TERMS CubeSat, NPS-SCAT, solar cell, CONOPS, space program budget, solar cell tester, radiation environment, program management | | | 15. NUMBER OF PAGES 83 |
| | | | 16. PRICE CODE |
| 17. SECURITY CLASSIFICATION OF REPORT Unclassified | 18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified | 19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified | 20. LIMITATION OF ABSTRACT UU |

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

NPS-SCAT CONOPS AND RADIATION ENVIRONMENT

Adam L. Hill
Lieutenant, United States Navy
B.S., University of Missouri, 2005

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SPACE SYSTEMS OPERATIONS

from the

**NAVAL POSTGRADUATE SCHOOL
June 2012**

Author: Adam L. Hill

Approved by: James H. Newman
Thesis Advisor

Daniel J. Sakoda
Second Reader

Rudolf Panholzer
Chair, Space Systems Academic Group

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

Solar cells are the primary energy-collection agents used onboard spacecraft converting energy from the sun into electricity. With solar cells being the main source of power for satellites, it is important to know how they operate and degrade when exposed to the harsh environment of low earth orbit. The objective of this thesis is to estimate the solar cell degradation that will be experienced on orbit due to radiation. This linked with the mission of the NPS-SCAT providing a quantitative measurement on orbit of how solar cells degrade over time can reduce risk of expensive national satellite by providing real-life solar cells exposure to threats of the space environment.

A secondary goal of this thesis is to build and present a representation of the CONOPs (concept of operations) that describes the functionality expected on orbit. Coordination with the software programmers as well as the staff to set robust functionality is the goal for the CONOPs. This software package will be programmed into the two 1U flight certified CubeSats as their standard programming once implementation and testing have been completed.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

| | | |
|------|--|----|
| I. | INTRODUCTION | 1 |
| A. | CUBESAT ADVANTADAGES | 1 |
| B. | PURPOSE | 6 |
| II. | NPS-SCAT PROGRAM MANAGEMENT | 9 |
| A. | PROGRAM MANAGEMENT | 9 |
| 1. | Budget | 9 |
| a. | <i>FY11 Budget Analysis</i> | 9 |
| b. | <i>Travel</i> | 11 |
| c. | <i>Equipment</i> | 11 |
| d. | <i>Contracts</i> | 13 |
| e. | <i>Indirect Cost</i> | 13 |
| f. | <i>Labor</i> | 13 |
| 2. | SCHEDULE | 14 |
| B. | ARCHITECTURE | 14 |
| 1. | Subsystems | 14 |
| a. | <i>FM430.</i> | 15 |
| b. | <i>MHX-2400.</i> | 19 |
| c. | <i>Clyde Space EPS.</i> | 20 |
| d. | <i>Beacon</i> | 22 |
| e. | <i>SMS.</i> | 24 |
| f. | <i>Solar Panels.</i> | 25 |
| g. | <i>Structure.</i> | 27 |
| C. | STUDENT WORKFORCE/CONTRACTING | 28 |
| III. | CONCEPT OF OPERATIONS | 33 |
| A. | MISSION | 33 |
| B. | OPERATIONS ON ORBIT | 36 |
| C. | GROUND STATION | 40 |
| 1. | Mission Operations Software | 41 |
| 2. | Ground Station | 41 |
| a. | <i>MHX2400 Ground Station</i> | 41 |
| b. | <i>Beacon Ground Station</i> | 42 |
| 3. | Ground Network and Data Base | 43 |
| D. | CONTINGENCY OPERATION | 43 |
| 1. | Power Management Failure | 43 |
| 2. | Loss of communications | 43 |
| 3. | Failed beacon antenna deployment | 44 |
| IV. | ORBITAL ENVIRONMENT | 47 |
| A. | SPACE ENVIRONMENT | 47 |
| 1. | Plasma | 47 |
| 2. | Orbital Debris and Meteoroids | 48 |
| 3. | Surface Degradation Hazards | 50 |

| | | |
|----|--|----|
| 4. | Perturbations | 51 |
| 5. | Orbital decay | 51 |
| 6. | Energetic Particles | 52 |
| B. | RADIATION ENVIRONMENT | 53 |
| 1. | Solar Cell | 53 |
| 2. | STK/SEET | 55 |
| 3. | NASA Solar Cell Radiation Handbook | 57 |
| 4. | South Atlantic Anomaly | 59 |
| C. | FUTURE WORK FOR NPS-SCAT | 60 |
| D. | SUMMARY | 61 |
| E. | CONCLUSION | 61 |
| | LIST OF REFERENCES | 63 |
| | INITIAL DISTRIBUTION LIST | 67 |

LIST OF FIGURES

| | | |
|------------|---|----|
| Figure 1. | Actual 2010 budget distribution..... | 10 |
| Figure 2. | NPS-SCAT stack [From 7]..... | 15 |
| Figure 3. | FM 430..... | 16 |
| Figure 4. | Clyde Space power supply diagram [After 9]..... | 18 |
| Figure 5. | MHX[From 11]..... | 20 |
| Figure 6. | Clyde Space EPS..... | 21 |
| Figure 7. | Cal Poly Beacon Rev 4..... | 23 |
| Figure 8. | SMS..... | 25 |
| Figure 9. | NPS-SCAT solar panels..... | 26 |
| Figure 10. | 1U CubeSat structure..... | 28 |
| Figure 11. | CONOPS start-up into status mode [From 24]..... | 34 |
| Figure 12. | NPS-SCAT flight mode [From 24]..... | 35 |
| Figure 13. | Beacon deploy diagram [From 24]..... | 37 |
| Figure 14. | Diagram of interrupt driven tasks [From 24]..... | 38 |
| Figure 16. | Probability of partial impact at 350 km..... | 49 |
| Figure 17. | Probability of partial impact at 500 km..... | 50 |
| Figure 18. | NPS-SCAT's Orbit lifetime estimate as a function of altitude.[After 22]..... | 52 |
| Figure 19. | STK "NASA electron flux" for a day..... | 56 |
| Figure 20. | STK "NASA proton flux" for a day..... | 57 |

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

| | | |
|-----------|---|----|
| Table 1. | NPS-SCAT Key Performance Parameters [From 4]..... | 8 |
| Table 2. | 2011 Initial Budget Allocation..... | 10 |
| Table 3. | Breakdown of major purchases..... | 12 |
| Table 4. | Texas Instruments MSP430F161x family of microcontrollers [From 8]..... | 17 |
| Table 5. | Test Cell 1, ITJ [From 17]..... | 54 |
| Table 6. | Test Cell 2[From 18]..... | 54 |
| Table 7. | Test Cell 4[From 20]..... | 54 |
| Table 8. | Combined total dose in rads at 350km and 50 mils shielding for one month..... | 56 |
| Table 9. | Calculated Fluence for 50 mils for electrons and protons for desired Altitudes at various shielding thicknesses..... | 58 |
| Table 10. | Solar Cell Radiation Handbook Calculations for Total Dose with Test Cell Analysis of percentage remaining at 350km 50degree[After 25]..... | 59 |
| Table 11. | Test Cell Analysis of percentage remaining at 500km 50degree for five years..... | 62 |

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

BCR - Battery Charge Regulator

DON - Department Of the Navy

Cal Poly - California Polytechnic University

CONOPS - Concept of Operations

COTS - Commercial Off The Shelf

CPU - Central Processing Unit

EDU - Engineering Design Unit

EELV - Evolved Expendable Launch Vehicle

EPS-Electrical Power System

ESP- Experimental Solar Panel

ESPA - (EELV) Secondary Payload Adapter

FY - Fiscal Year

I²C - Inter-Integrated Circuit

MHX - Micro-Hard transceiver

MHZ - Megahertz

NPS - Naval Postgraduate School

RTOS - Real-Time Operating System

SCAT - Solar Cell Array Tester

SEET - Space Environment & Effects Tool

SERB - Space Experiment Review Board

SEU - Single event upset

SMS - Solar cell Measurement System

SSAG - Space Systems Academic Group

STARE - Space-based Telescope for the Active Refinement of
Ephemeris

STK - Satellite Tool Kit

I. INTRODUCTION

A. CUBESAT ADVANTADAGES

Very small satellites are transitioning from being educational projects and technology demonstrators to being viable operational architectures. CubeSats in particular are also making this transition to the operational realm through multiple avenues. NPS's first CubeSat, NPS-SCAT, still operates within that operational proof-of-concept design model, but will have the ability to actually test solar cells on orbit at a fraction of the cost of large satellite programs.

Program organization and the philosophy of small satellite programs benefit from the ability to reduce cost while still meeting requirements of their programs within reduced timeframes. Shorter times required for research and development throughout the manufacturing of the satellite reduces the overall associated cost. This allows greater flexibility, as well as allows players in the space market who would otherwise not be able to enter due to budgetary limitations. Important to NPS is that CubeSats allow educational organizations the ability to give students the capability for hands on experience from conception to operations on orbit of an actual satellite.

Small-spacecraft missions have established effectiveness in space-based scientific and engineering programs. CubeSats further that role by developing streamlined programs with less traditional approaches than their larger spacecraft counterparts. Focused project teams with set goals could meet desired capabilities within a

standard CubeSat form with reduced schedule and cost. The NPS-SCAT project follows this model by developing, designing, and building the satellite with a dedicated experiment while leveraging as much as possible from the commercial market. Although the time frame for completing NPS-SCAT has not been as short as possible due to the nature of the learning environment on its first CubeSat, as well as NPS's goal of building a robust CubeSat program, it has certainly accomplished its goals of involving students in all aspects of satellite design, build, integration, and test.

Low-cost space systems are manufactured by maximizing the use of existing components and commercial-off-the-shelf (COTS) technology and minimizing developmental efforts involved. Sixty percent of NPS-SCAT subsystems are COTS products. Companies specializing in the CubeSat subsystems have helped reduce the acquisition costs due to the developmental and testing expenses done externally from the project. This has helped increase the numbers of CubeSats in development throughout the world. Engineering development units for some CubeSats are not built before actual flight unit construction due to the added expense to test prototype electronics for the sole purpose of validating flight hardware. NPS has built an NPS-SCAT EDU and retested all subsystems within it as part of developing a robust CubeSat program to leverage future educational opportunities. NPS-SCAT's development was in part to generate a low-cost CubeSat capability using CubeSat standard products. This capability supports the NPS small-satellite program in its hands-on education while doing focused research of national interest with increasing

complexity over time. To maintain the benefit from NPS-SCAT experience requires the maximum use of existing components and COTS technology.

Launch cost and limited access to space are also major areas that can be beneficial for small satellites over their larger scale siblings. Launch costs for a dedicated small rocket or the shared expense when incorporated as a secondary payload can still remain high, however the cost involved is greatly reduced when compared to that of a large rocket. The development of a broad array of secondary payload capabilities on expendable launch vehicles provides increased access to orbit for many different kinds of payloads. For example, the development of the EELV Secondary Payload Adapter (ESPA) ring as a secondary payload deployment location should decrease the cost of access to space while allowing access to space for organizations that would not be able to afford their own rocket [1].

As technology improves, and if Moore's law continues to hold, many electronic devices will continue to get smaller, require less power, and be more capable. The ability of CubeSats to be more than an educational tool and move further into operational missions should be possible. For example, NPS is currently working with Lawrence Livermore National Laboratory to integrate an optical payload with the Boeing Colony II Bus. The operational concept of STARE (Space Telescope for the Actionable Refinement of Ephemeris), a 3U CubeSat, is being developed to prove the capability to conduct Space Situational Awareness. CubeSats are commonly used as scientific and

technology drivers due to their limited size and capabilities. The improvement of electronics and other systems could open up new applications for CubeSats such as commercial mobile communications and remote sensing. CubeSat functionality has increased to its current level because of the availability of increased space-compatible computational power and memory. These advances have already led to increased capabilities and an increasing number of missions using CubeSats.

There are risks involved that can counter or even outweigh the benefits that are achieved through using CubeSats. The reduction of redundancy within the spacecraft limits components available as backup. With the lack of redundancy, a design must rely on multifunctional subsystems vice additional back-ups that could provide functionality if something went wrong during a mission. Failures do not simply manifest themselves ahead of time. Risk mitigation starts with testing and performance validation. CubeSat programs are usually more risk tolerant than larger programs, resulting in the potential for more failures, not just from low probability events but also from failure modes which might have been found with a more expensive and robust test plan. When the goal of a small satellite program is to produce spacecraft cheaper and faster, this could lead to failures caused by lack of sufficient resources to thoroughly test, simulate, or review the work and processes. These errors are more likely to occur when a program is operating near its budget limit or under scheduling pressures. The heart of the issue is the allocation of cost and schedule throughout a program. When cost and schedule controls the advancement of the

spacecraft design instead of being driven by performance characteristics and reliability the mission objectives have a lower probability of success. Spacecraft that are designed faster and cheaper result in lower costs per mission and have shorter development times, however these benefits may be achieved at the expense of reliability on orbit. NPS-SCAT has been afforded ample time and resources to thoroughly develop, build, and test NPS-SCAT. Other inherent risks are the scalability of technology used in spacecraft as a proof of concept for future flight hardware or software for a major program. Cost savings may not be obtainable due to the reengineering required to implement the technology into a more complicated system [2].

One of the advantages of a CubeSat-sized satellite is the ability to strengthen the core level of space industry knowledge. The educational experience allows the student exposure to the concepts of acquisition, design, manufacture, test, launch, and operations. This is in accordance with the 2010 National Space Policy, which calls for the need to develop and retain space professionals. The increased access to space, along with the reduced cost per satellite, allows educational institutions to get involved and develop expertise in space engineering for young engineers. This group of individuals helps generate the experience base that meets the goals established within the National Space Policy. The National Space Policy calls for the cooperation of industry and academia to establish standards, create opportunities for the space workforce, while developing, maintaining, and retaining skilled space professionals in both government and commercial workforces [3].

B. PURPOSE

The objective of this thesis is to analyze the anticipated radiation environment and the degradation effects of that radiation environment on the test solar cells. NPS-SCAT's objective is to provide two 1U CubeSats capable of operating and testing solar cells in Low Earth Orbit (LEO). With solar cells being the primary energy-collection agents used onboard spacecraft, it is important to know how they operate and degrade when exposed to the harsh environment of LEO. The secondary thesis objective is to build and present a representation of the CONOPS explaining NPS-SCAT's expected on-orbit functionality. The objective is to program as much robust functionality into the satellite as possible. Coordination with the software programmers and the satellite team is essential for the successful integration of software and hardware. This software CONOPS will be programmed into the two 1U flight CubeSats as their standard programming once implementation and testing has been completed

All aspects of the design, assembly, integration, and testing have been captured for follow-on CubeSat projects. NPS-SCAT adheres to the CubeSat standard and uses Commercial off the Shelf (COTS) to the maximum extent possible. This will enable rapid and effective use of the bus for future flight opportunities. The NPS-SCAT Program has developed Key Performance Parameters (KPP) to guide it towards its goals. See Table 1 for a list of the NPS-SCAT KPPs [4].

NPS-SCAT is an educational platform for students to gain experience in satellite design, integration, testing,

and operations. Every aspect of the project has involved students as program and subsystem managers and engineers. As the program manager of the satellite in the final phase of the build, the author was involved in the management of the budget and schedule, as well as helping with integration and testing.

As of this writing, NPS-SCAT has been scheduled for launch in July of 2012 aboard the fourth Educational Launch for Nano-satellites (ELaNa IV) mission using a Falcon 9 as the launch vehicle. The delivery date for integration is set for March 2012. NPS-SCAT has been approved by the Department of Defense (DoD) Space Experiment Review Board (SERB) for flight. SERBs happen every year for each branch of the military and provide a means for service experiments to obtain flight opportunities. After the service SERBs, experiments go through the DoD SERB process for priority ranking. Finally the Space Test Program (STP) seeks flight opportunities for approved experiments. The current NPS-SCAT launch date offers ample time to finish and test the flight software.

| KPP Number | KPP |
|-------------------|--|
| 001 | <i>The satellite development program shall provide NPS students with an education in the satellite design process, integration, testing, and full life cycle of a space flight system.</i> |
| 002 | <i>The satellite shall utilize a 1U Pumpkin CubeSat architecture and Commercial Off the Shelf (COTS) hardware whenever possible.</i> |
| 003 | <i>The solar measurement system shall be capable of obtaining solar cell I-V curve data to include solar cell current, voltage, temperature, and sun angle no less than once per orbit.</i> |
| 004 | <i>The satellite shall be able to communicate Telemetry, Tracking and Command (TT&C) and Payload data to the NPS ground station using an S-band radio (primary transmitter) and/or UHF beacon (secondary transmitter).</i> |
| 005 | <i>The satellite shall transmit TT&C and Payload data regularly (aka "in the blind") via the UHF beacon and transmit data when a communications link is established with the ground station via the S-band radio.</i> |
| 006 | <i>The satellite shall be capable of being launched via a CubeSat standard compatible deployer (like a P-POD) on an Evolved Expendable Launch Vehicle (EELV).</i> |
| 007 | <i>The satellite shall operate continuously in orbit upon launch and have a mission life of 1 year.</i> |
| 008 | <i>The satellite development program shall establish the CubeSat program at NPS by creating a CubeSat working group, small satellite process and procedure development, and establishing an engineering support structure.</i> |

Table 1. NPS-SCAT Key Performance Parameters [From 4]

II. NPS-SCAT PROGRAM MANAGEMENT

A. PROGRAM MANAGEMENT

The Program Manager responsibilities included full budget authority and the program schedule. The budget for Fiscal Year 2011 (FY11) was about \$43k for equipment, labor, indirect cost, contracts, and travel. NPS utilizes the Kualī Financial System (KFS) as the campus financial management program. All aspects of individual program financials are recorded here. The NPS-SCAT Program also kept a record of all expenditures to check against data entered into KFS from the school. This has served as a sound policy as there have been two clerical errors found during FY11

1. Budget

The FY11 budget analysis consists of funds expended to support NPS-SCAT. These funds were expended between September 2010 and September 2011. The FY11 funding received for NPS-SCAT is available until September 2011.

a. FY11 Budget Analysis

For FY11, the NPS-SCAT program budget was \$43,062. The initial allocation of funds can be seen in Table 2. Allocations of funds are set at the start of the year as an estimate of how the funds will be used.

| Cost Type | Estimated Funding |
|------------------|--------------------------|
| Travel | \$7,861.34 (18%) |
| Equipment | \$9,850.33 (22%) |
| Contracts | \$5,200 (12%) |
| Labor | \$11,149.61 (26%) |
| Indirect Costs | \$9,000 (21%) |

Table 2. 2011 Initial Budget Allocation

The initial allocation into specific budget areas must be monitored, and changed as necessary throughout the year. The final value spent versus the funding available is the true gage that matters. Figure 1 shows the FY11 actual budget distribution.

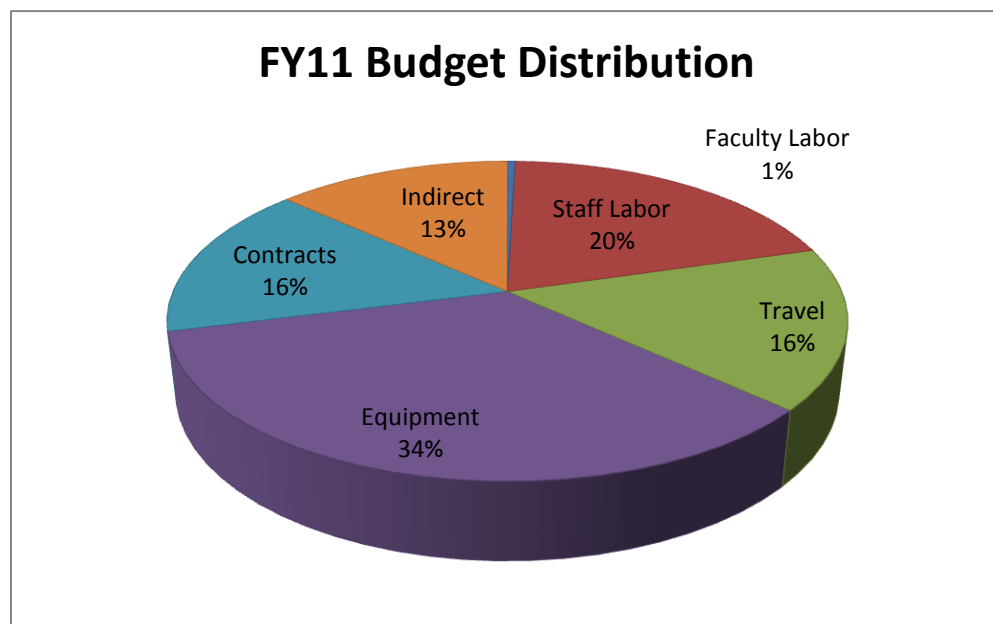


Figure 1. Actual 2010 budget distribution

b. Travel

Travel funding was set in anticipation for accommodating travel to attend the following conferences, the CubeSat Workshop in San Luis Obispo, the Small Satellite Conference in Logan, Utah, and the Department of the Navy (DoN) Space Experiments Review Board (SERB).

Travel to the conferences was not mandatory for the NPS-SCAT team members, but provided opportunities for students to present poster sessions and learn more about small satellite activities. For FY11, conference travel was minimal. Four members traveled on the program budget to the various conferences available. Time and workload constraints limited the attendance to the conferences. NPS-SCAT sent one member to the DON SERB to brief the project. Overall very little of the allocated travel budget was spent in FY11.

c. Equipment

Major equipment purchases were for the following: a new Clyde Space Version 2 EPS (electrical power system), two EPS battery boards, beacon board manufacturing, beacon board component population, and staking compound. There were many other purchases that fall under this expense category but do not carry the significance in cost that these items do. These major purchases constituted 91% of the total equipment purchases and 23% of the program budget. See Table 3 for a list of major purchases.

| Major FY 11 Purchases | | | | |
|-----------------------|----------|-----------------------------|----------|----------|
| | EPS V2 | EPS daughter battery boards | Beacon | Staking |
| Expense | 4,629.00 | 2,320.00 | 1,398.85 | 1,022.00 |
| | | | 934.70 | |
| Total | 4,629.00 | 2,320.00 | 2,333.55 | 1,022.00 |

Table 3. Breakdown of major purchases

All of the items purchased were considered necessary for the program to succeed. The purchase of the two EPS daughter boards was needed when the batteries were unintentionally and completely drained, reducing the battery capacity below what was acceptable for flight. The Clyde Space Version 2 EPS purchase was also a replacement purchase. It replaced the flight unit 2 EPS Version 1 that had a known current drain of one milliamp. The Version 2 Clyde Space EPS was designed to eliminate this drain on the battery. The beacon board that was designed in collaboration with Cal Poly was also manufactured. The program might have saved money by allowing Cal Poly to populate the boards by hand. However, the NPS-SCAT team agreed with Cal Poly that professional component population would add more consistency and reliability into the build. This however also added an additional expense that the program had to cover. It was decided that it was worth the added benefit.

Other purchases for this spending period were used to build the flight unit #1 and flight unit #2.

d. Contracts

At the request of the sponsor and consistent with their educational goals for NPS-SCAT, there was a \$5,000 transfer to the Naval Academy to assist in travel in support of the development of their educational CubeSat program. The other \$150 listed on the FY11 budget spreadsheet was reimbursement for the CubeSat conference fees, considered contracts by the NPS financial system.

e. Indirect Cost

These costs are charged against all sponsored programs to help recover the administration and facilities costs that cannot be directly billed to a project. It is a fixed rate charged against the account, for FY11 it was 30.97%. It is assessed against labor, travel, and procurements, with a few exceptions.

f. Labor

The primary source of labor for NPS-SCAT is a mix of military students and undergraduate interns from other schools. There were two military students working on project during FY11. The project also had occasional support of two interns from Cal Poly, and full-time software support from a California State University of Monterey Bay intern. The interns are paid an hourly wage and work when they can during the school year and full time during the summer. Intern hours for FY11 totaled 688 hours, for a total cost of \$11,163.33. Labor accounted for 26% of the total NPS-SCAT budget allocation for FY11 [4,6].

2. SCHEDULE

The scheduling process in an educational environment was discussed in the student workforce section. The remaining tasks for NPS were presented in Kevin Smith's thesis [6]. Time requirements were set based on the original integration delivery date in December, 2011. There have been multiple delays in the delivery date; however NPS-SCAT is still expected to be complete in the December timeframe. It will then sit on the shelf until the flight delivery.

B. ARCHITECTURE

1. Subsystems

Figure 2 shows the sub-component stack and how each component interacts as well as the orientation. A brief description of each individual sub-systems starting from the bottom or -z face and working up are listed in the following sections.

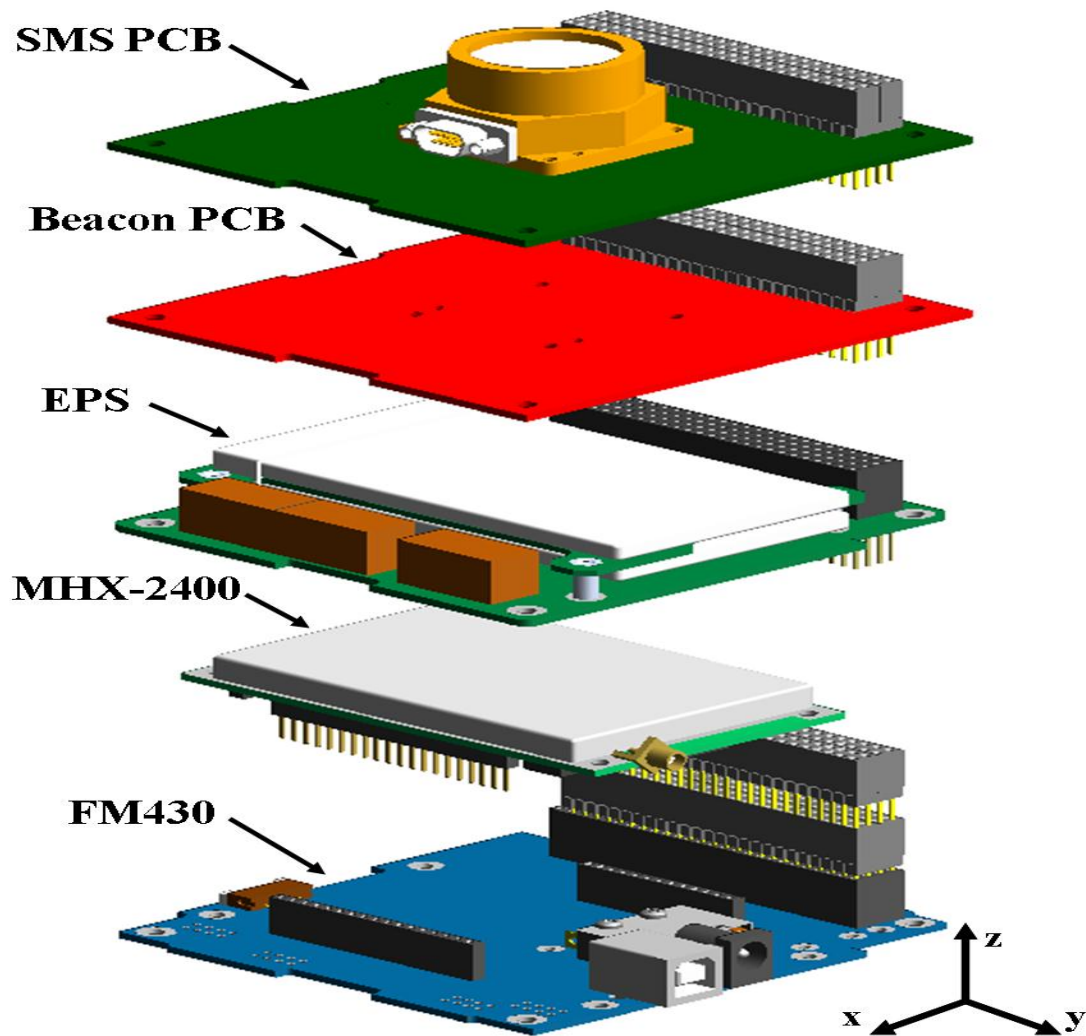


Figure 2. NPS-SCAT stack [From 7]

a. FM430.

The FM430 is the command and data handling subsystem which contains the central processing unit (CPU) for NPS. The FM430 can be seen in Figure 3. The Engineering Design Unit (EDU) uses an MSP430F1612 microcontroller as the main chip that holds the software for the satellite. The microcontroller runs the Salvo RTOS (real time operating system) and is written in the C programming

language. Flight unit #1 will utilize the MSP430F1612, but flight unit #2 will use an MSP430F1611. The FM430 has been discontinued and is no longer in production, so the program is limited to the quantities on hand. There is one FM430 with a F1612, used for flight unit #1, and two FM430s with F1611's; one of these is for flight unit #2 and the other is a flight spare.

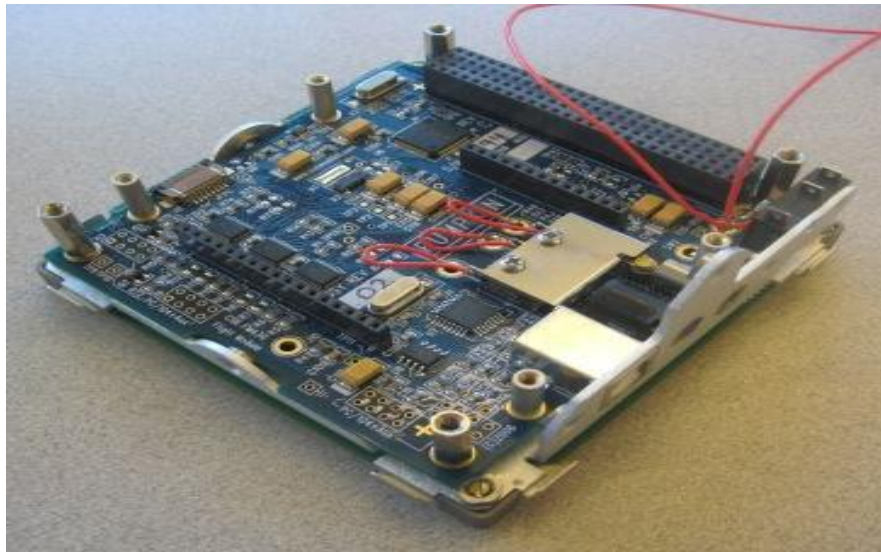


Figure 3. FM 430

The differences between these two chips are minor. They both have the same pin layout and functionality. The differences are listed in the following Table 4.

| | MSP430F1611 | MSP430F1612 |
|------------------------|-----------------------|----------------------|
| Memory (FLASH) | 48KB | 55KB |
| Main: Interrupt vector | 0FFFFh-0FFE0h | 0FFFFh-0FFE0h |
| Main: code memory | 0FFFFh-04000h | 0FFFFh-02500h |
| RAM (total) | 10KB 038FFh-01100h | 5KB 024FFh-01100h |
| Extended | 8KB 038FFh-01900h | 3KB 024FFh-01900h |
| Mirrored | 2KB 018FFh-01100h | 2KB 018FFh-01100h |

Table 4. Texas Instruments MSP430F161x family of microcontrollers [From 8]

The data show that the F1611 has less flash memory than the F1612 but more RAM. NPS-SCAT does not use the entire memory capability of the F1612 with our flight code, so the F1611 flight unit should be more than capable of handling the capacity requirements of the code. The code currently uses about 38 KB of FLASH and 3.7 KB of RAM, so it is within the parameters associated with the 1611. FLASH usage should not theoretically increase or decrease significantly with upcoming code changes. Aside from the differences in the microcontroller mentioned above, several hardware modifications were accomplished to the board before placing the FM430 into flight units #1 or #2.

The separation switch, located on the structure, had to be connected to the FM430. The function of the separation switch is to isolate the voltage regulators from

the battery charge regulators (BCRs) and battery. There are three pins on the separation switch, which are physically located on the inboard +Y-axis face of the Base Plate Assembly structure. There are three soldering pads on the FM430 that correspond to the three pins on the switch. To enable full-functionality of the separation switch a jumper wire was used to connect these matching pins to the respective pads. For integration purposes, a separation switch connector is used as an intermediate between the two. Once the separation switch is active, special precautions must be taken when handling the satellite, as the CubeSat foot will activate the satellite. This has consequences, especially if the Pull-Pin is inserted into the satellite, which means that the Pull-Pin switch is OPEN. The EPS schematic is shown in Figure 4. Note that if the separation switch is CLOSED and the Pull-Pin is OPEN, the resulting circuit may cause damage to the Battery Charge Regulators (BCR).

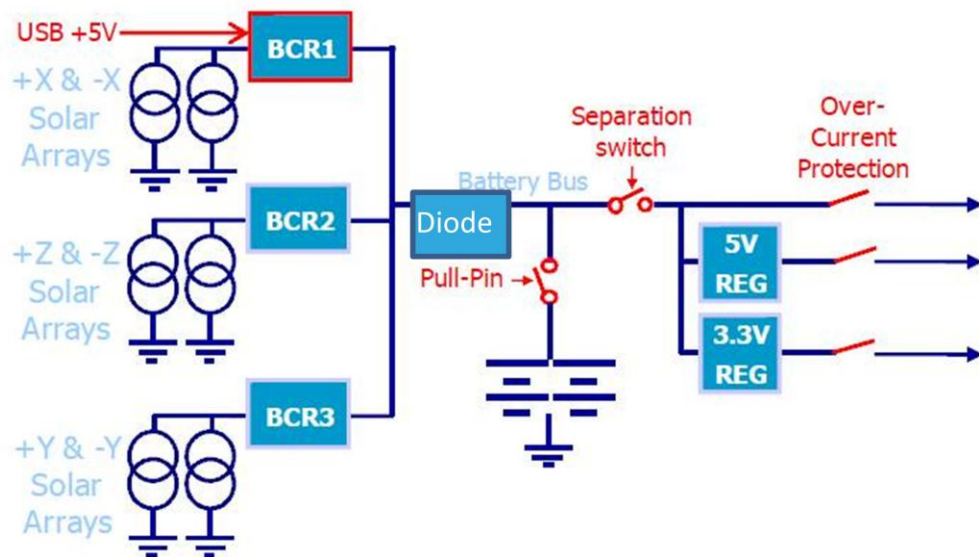


Figure 4. Clyde Space power supply diagram [After 9]

As with the separation switch the Pull-Pin connection also had to be connected. The Pull-Pin isolates the battery from the BCRs and voltage regulators. It is similar in make-up to the separation switch as it also has three pins. The physical location of the switch is on the FM430 PCB, underneath the MHX-2400. There are also three pads that correspond to the three pins of the switch. A simple wire connection needs to be made to enable the functionality of this switch [10].

b. MHX-2400.

The MHX 2400 is the primary communication system for NPS-SCAT. Operating in the S-band at 2.44 GHz, the MHX-2400 will allow the satellite to establish a connection with the ground station located on the NPS campus in Monterey, California to downlink the satellite telemetry. The MHX-2400, seen in Figure 5, is a frequency-hopping, spread-spectrum module that has a maximum output power of one watt [11]. This subsystem is plug-and-play when it comes to integration. The pins on the bottom of the MHX-2400 module fit into the specially-made connectors located on the FM430.



Figure 5. MHX[From 11]

The MHX-2400 uses a patch antenna, which is located on the -Z-axis face of the Base Plate Assembly. Before operating the satellite, an antenna must be connected to the MHX-2400 antenna coaxial connector. Without an antenna, the RF energy has no place to go but back inside the MHX-2400 components, possibly causing these components to fail. For further data on the MHX2400, see Cody Mortensen's thesis [12].

c. Clyde Space EPS.

The EPS for NPS-SCAT is the Clyde Space 1U power system. The EPS consists of two components, the EPS board and the battery daughter board, as seen in Figure 6. The EPS has two bus voltages operating at 5.0V (volts) and 3.3V. The battery has an operating output voltage from 6.2V to 8.26V [13]. Figure 6 shows the integrated Clyde Space EPS.

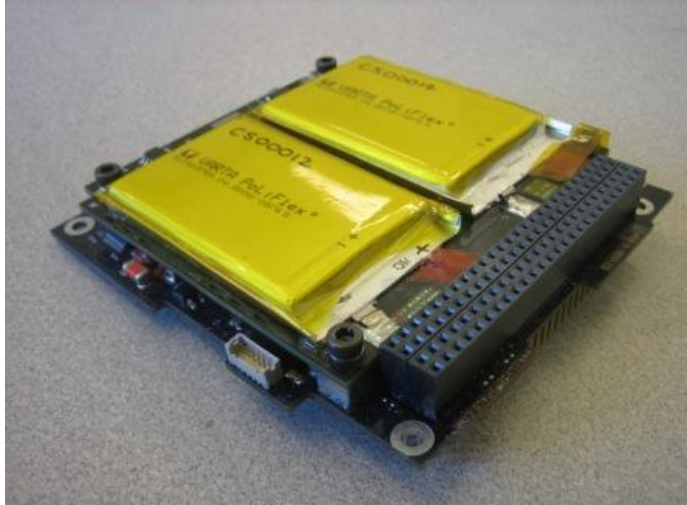


Figure 6. Clyde Space EPS

The battery daughter board has two Lithium Ion Polymer battery cells connected in series. The board is capable of providing battery voltage, current, and temperature telemetry for health and status for each battery cell.

There are two versions of the Clyde Space EPS, the EPS1 and the EPS2. The EPS1 is located in the EDU and has a leakage current when the pull-pin is removed. The EPS2 has fixed this flaw. We have one EPS2 for each of the flight units. The need for software testing is present because of the differences in telemetry assignment within the EPS hardware. The EPS telemetry is accessed using an I²C (inter-integrated circuit) bus. An analog to digital converter is used onboard the EPS board to convert the current, voltage, and temperature data measured on the EPS to digital format that can be read by the MSP430.

About once a month, the batteries need to be checked and, if necessary, charged to within the storage voltage levels (7.6 V to 6.4 V). The charging procedure is

outlined in the Clyde Space Manual. For more information on the EPS, see Jamie Fletcher's master's thesis [15].

d. Beacon

The secondary communications system operates at 437 MHz, within the amateur band, 430-438 MHz, and is being developed in collaboration with California Polytechnic State University in San Luis Obispo (Cal Poly). This system will function primarily as a beacon, transmitting telemetry consisting of system health parameters and a packet of payload data; however it will also receive command uplinks from NPS for satellite housekeeping [16].

The final Beacon PCB is Cal Poly's revision 4 seen in Figure 7. The beacon transmits in a format known as the AX.25 protocol. This is a type of protocol that can be interpreted by the amateur radio operators which will allow amateur radio operators to receive NPS-SCAT data and send it to NPS. In addition, the beacon also transmits its call sign, K6NPS, in Morse code. The software used to receive the beacon transmissions is called MixW and is installed on the amateur band ground station computer.

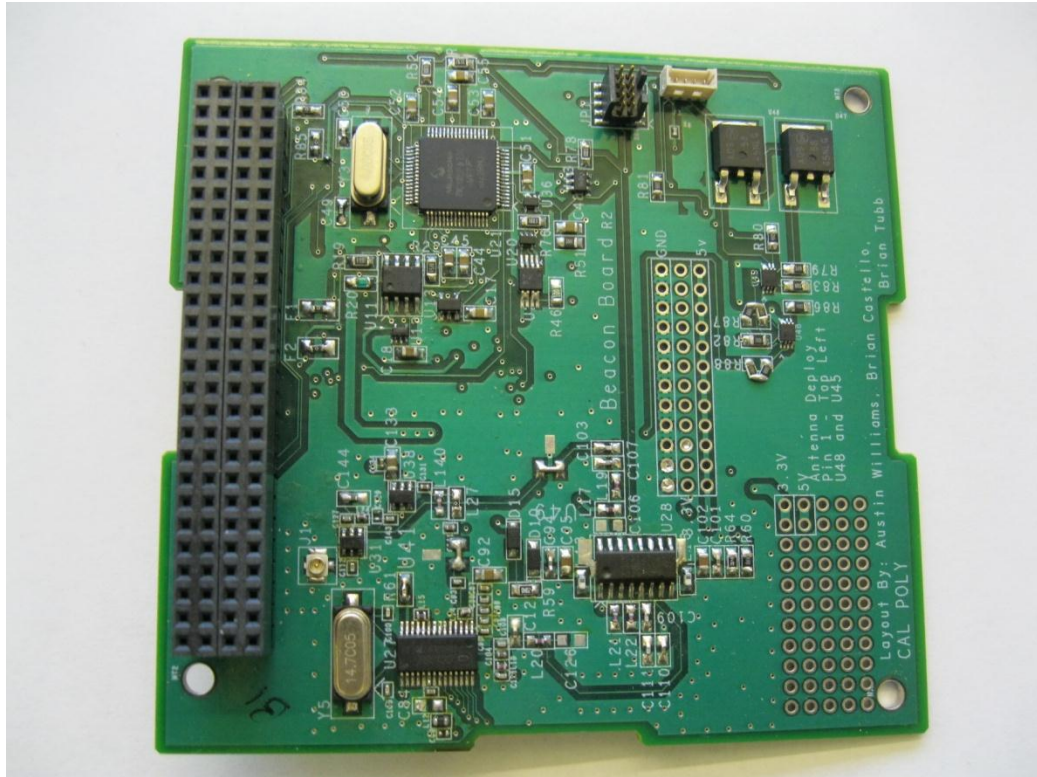


Figure 7. Cal Poly Beacon Rev 4

The Beacon antenna is attached to the +Y-axis solar panel. It is a half-wave dipole antenna, which consists of two lengths of spring steel piano wire that are each $\frac{1}{4}$ wavelength in length. The expected transmitting frequency for the beacon is around 437 MHz, which requires the antenna length to be around 17 cm long. The antennas are soldered to the +Y-axis solar panel after first compressing a copper tube to the end of the antenna. There are 9 hooks that are used to stow the antenna for launch. The antennas are stowed by tying fishing line to the ends of the antenna. The fishing line is passed through a segment of nichrome wire and then tied back to the antenna end. The nichrome wire heats up on-orbit to melt the

fishing wire, releasing the ends of the antenna. For further information on the beacon see Cody Mortensen's thesis [12].

e. SMS.

The payload for the NPS-SCAT is the Solar Measurement System (SMS), as shown in Figure 8. It consists of three major components; the SMS circuit board, the Experimental Solar Panel (ESP), and the sun sensor. These three sub-systems had to be designed and integrated into the 1U CubeSat structure, while leaving room for the other subsystems. This was one of two subsystems that is not COTS and the first subsystem built by NPS. The solar panels have harnesses plugging into the SMS, which in turn route the solar panel power to the EPS. It also serves as the structure holding the sun sensor. The ESP consists of four solar cells that the SMS will evaluate on orbit. The four NPS-SCAT cells that were chosen to be tested include: Spectrolab Improved Triple Junction (ITJ) [17], EMCORE Triple Junction with Monolithic Diode Solar cell (BTJM) [18], Polycrystalline silicon [19] and Spectrolab Triangular Advanced Solar Cell (TASC), an Ultra Triple Junction Cell (UTJ) [20].

Further SMS information and design can be found in Rod Jenkins' thesis [22].

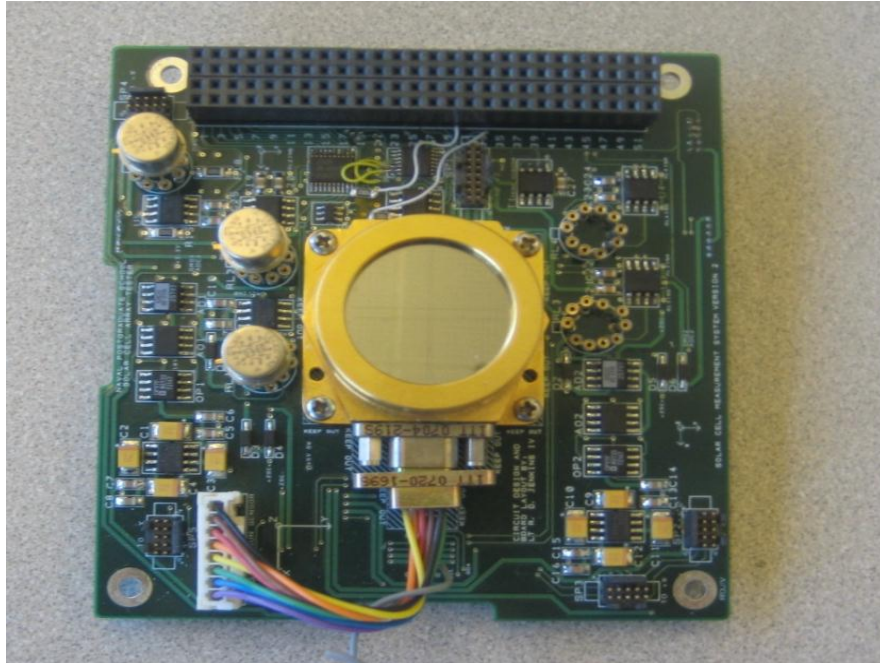


Figure 8. SMS

f. Solar Panels.

There are a total of six solar panels as seen in Figure 9. Three of them ($\pm X, -Y$) are exactly the same and contain the large area Spectrolab ITJ CIC. The $-Z$ -axis solar panel has a cut-out for the patch antenna and eight Spectrolab UTJ TASC. The $+Y$ -axis solar panel contains the Beacon antenna, deployment circuitry, and 8 Spectrolab UTJ TASC. These solar panels comprise the energy collection system for providing power to the Clyde Space EPS described above and are described separately from the EPS as they were designed at NPS, as opposed to being a COTS product. The $+Z$ -axis solar panel is the Experimental Solar Panel and houses the four experimental solar cells and has a cutout for the sun sensor.

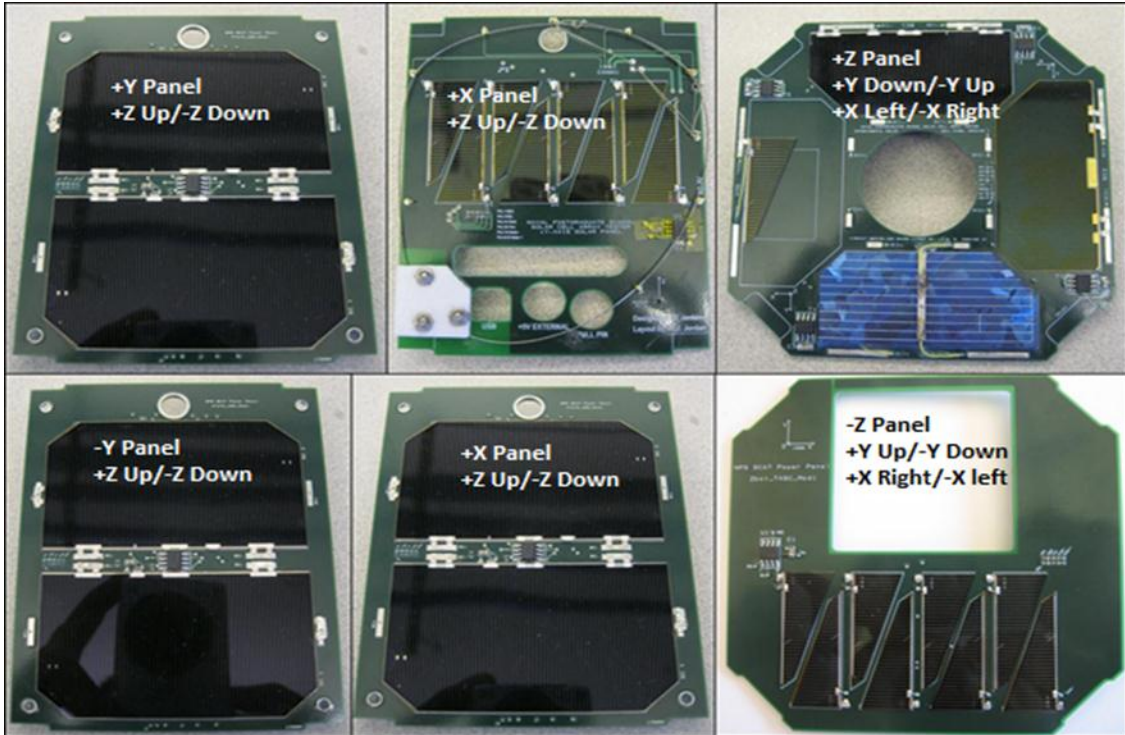


Figure 9. NPS-SCAT solar panels

a. Temperature Sensors. The component used to measure temperature on the solar panels is a MAX6633 digital temperature sensor. It uses I²C to relay the temperature data to the MSP430.

b. Connectors. The solar panels are all connected to the SMS via Samtec connectors. These connectors vary depending on the solar panel in question. All of the non-experimental solar panels ($\pm X$, $\pm Y$, $-Z$) use a 10-pin Samtec connector; the $+Z$ -axis solar panel uses a 16-pin Samtec connector. In order to prevent the solar cells from becoming forward biased, a Schottky rectifier was placed in-line in the connector. A forward biased solar cell acts like an LED and will eventually glow red with enough reverse current.

c. Solar Cells. The $\pm X$, $-Y$ solar panels have the Spectrolab CIC ITJ solar cells, large area cells with cover glass. They have a built in diode to prevent them from individually being reverse biased. The $-Z$ -axis and $+Y$ -axis solar panels each have eight Spectrolab TASC UTJ solar cells, small triangular cells without cover-glass. The solar panels are described in Rod Jenkins' thesis [22].

g. Structure.

The CubeSat structure is a Pumpkin, Inc., CubeSat Kit COTS component, seen in Figure 10. It is made out of sheet aluminum and the external fasteners are stainless steel. The bottom of the structure is the Base Plate Assembly and houses the separation switch and holds the FM430. The eight CubeSat feet and four rails that slide along the inside of the P-POD are hard anodized to prevent galling when in contact with the CubeSat launcher. The rest of the structure is alodine, which is an electrically-conducted surface finish. A grounding strap located on the FM430 serves the purpose to link the FM430 ground to the structure [10].

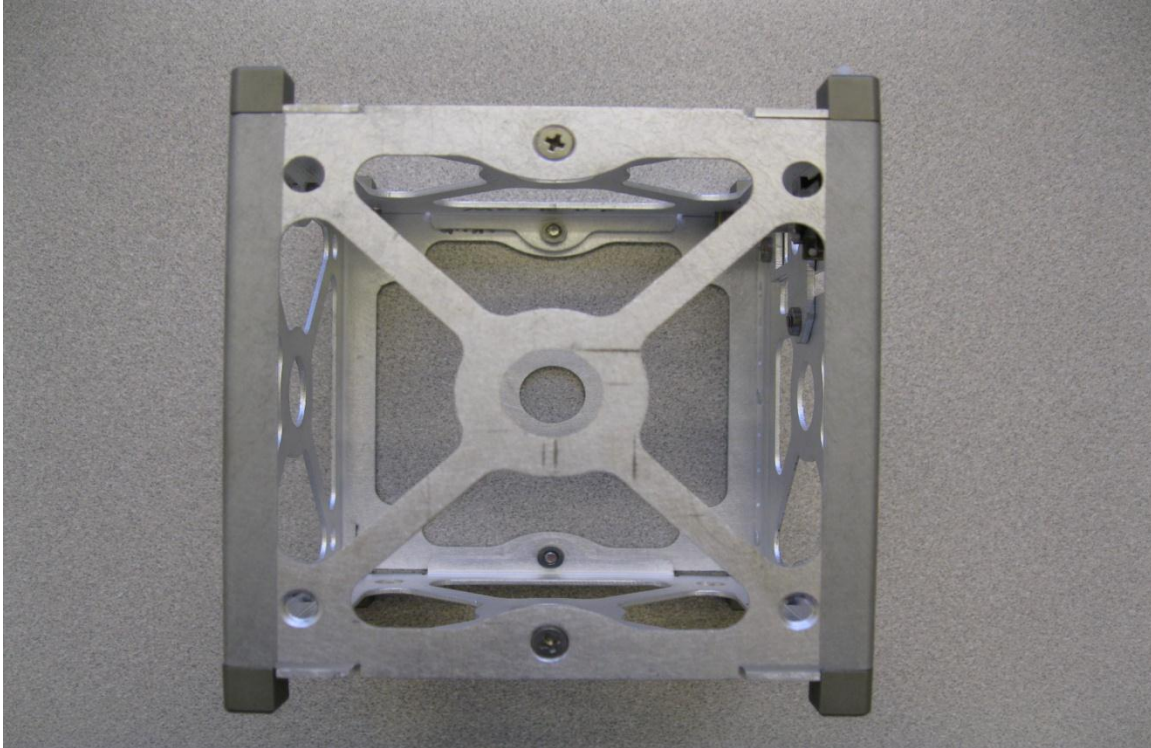


Figure 10. 1U CubeSat structure

C. STUDENT WORKFORCE/CONTRACTING

The student workforce is an important part of any university program. There are both advantages and disadvantages to the use of student labor for a satellite program, and it requires planning and involved management to optimize the tradeoffs. The primary advantage to student labor is the knowledge and experience gained by the student as part of the educational process, as well as the low cost of the labor. Disadvantages of student labor include inexperience, frequent turnover, and limited availability. However, with proper management these disadvantages can be overcome or at least minimized.

The chief objective of the NPS-SCAT program is to facilitate the space education of the NPS student

population. Due to this, it makes practical sense that students would perform the majority of the tasks associated with the design, management, and construction of the satellite. On the NPS-SCAT team, individual students were responsible for the design, testing, and integration of the satellite. Additionally, the team had a student responsible as the program manager. Frequent interaction between our team ensured that each participant gained understanding of a good portion of the breadth of satellite design.

The members of the NPS-SCAT team have come from varied military and civilian backgrounds, but the overwhelming majority had not had prior experience in the space industry. Therefore, the required knowledge and experience is gained from the academic curriculum, through self-study, "on-the-job" training, and finally through interacting with permanent support engineers associated with the Space Systems Academic Group (SSAG). Gaps in capability can exist when students join the development team before they have gained the requisite knowledge or do not get a quality handover from the previous group. A key to overcoming these weaknesses is to understand the institutional knowledge and experience that is available from professors, staff engineers, and support staff. One of the most important lessons learned from this experience was to enlist help of the staff early in the planning process. The staff should be encouraged to attend some, if not all, of the team's meetings to provide their perspective and insight. Formalizing a cohesive unit between the design team and staff is essential for prolonged success within the program. Documentation will help to capture any inputs

during meetings made towards satellite improvements. It will also provide a starting point for new members of the team to seek assistance.

Another drawback to using student labor is their high turnover rate. NPS-SCAT students experience approximately one year on the team on average before graduating. Each time a member leaves there is a risk that not only his experience will be lost, but also that any knowledge developed by the member will disappear as well. Managing transitions to ensure that a member's contributions are documented and that responsibilities are assumed by another member of the team is a significant challenge. It became clear during this last team transition that the importance of having a standard procedure for outgoing personnel to follow was essential. The new team struggled on multiple occasions to relearn multiple subsystems after the respective subsystem expert transitioned from NPS.

A hard fact to get conditioned to as a project manager in a student-centric environment is that student labor can never be assumed available. Students join a satellite development team to be a part of something interesting that will have a lasting impact. At NPS, it is up to students to choose the projects they would like to work on. Students will always have conflicts between classes, other projects, and personal lives that will limit the time available for the project. As class sizes for the Space Systems curricula fluctuate, the number of students available for thesis work can cause reductions within some programs. NPS-SCAT had six students in 2010 and then transitioned to the two who essentially finished the project in 2011. Unless an NPS

Space Systems student from the class graduating in 2012 decides to join the team, the final integration and software testing will be completed by the single remaining university intern with help from the NPS staff. It is important to account for this factor when establishing development timelines and work and meeting schedules. Development timelines that are too aggressive become unrealistic in a student environment.

NPS-SCAT also did some collaborative work with Cal Poly to create the beacon board. The boards were completed with the utmost professionalism but coordination between two educational organizations requires constant supervision as well. The scheduling conflicts experienced internally within NPS were multiplied when working with Cal Poly as NPS uses the quarter system and Cal Poly uses the semester system. One approach to resolve this dilemma is to establish task oriented metrics for measuring progress rather than a simple chart depicting start/stop dates. This allows progression at an appropriate student pace while allowing for measurable progress toward the goal of satellite completion.

THIS PAGE INTENTIONALLY LEFT BLANK

III. CONCEPT OF OPERATIONS

A. MISSION

The Concept of Operations Plan (CONOPS) provides guidance to Software Engineers for developing and employing system interoperability. Coordination with the build team and staff encompassing the desired operations on orbit generated a flow diagram describing the operation of the spacecraft as determined by requirements and capabilities. There are two distinct paths within the CONOPS plan. Both require the removal of the Remove Before Flight (RBF) pull pin and the closing of the separation switch, on one of the CubeSat feet, which allows power to be available to energize the FM430. During power-up, all the subsystems are set to off. Salvo schedules the base program that operates on the FM430, starts and initiates the Universal Serial Bus (USB) interface, and waits 20 seconds for a desired key input from the user. If the key code is received, the satellite goes into a Status Mode for ground checkout.

Status Mode allows access to the first of the two modes of the satellite. This mode is designed for ground checkout of the spacecraft while it is plugged into a USB, allowing almost full functionality of the spacecraft without having to necessarily radiate through either antenna. The Status Mode is designed for status checkout while charging the battery, giving housekeeping data every 3 seconds. Once in Status Mode, a designated NPS-SCAT password can be entered at any time to allow access to the

command functionality. Figure 11 shows the flow diagram encompassing the power up through the Status Mode of the spacecraft [23].

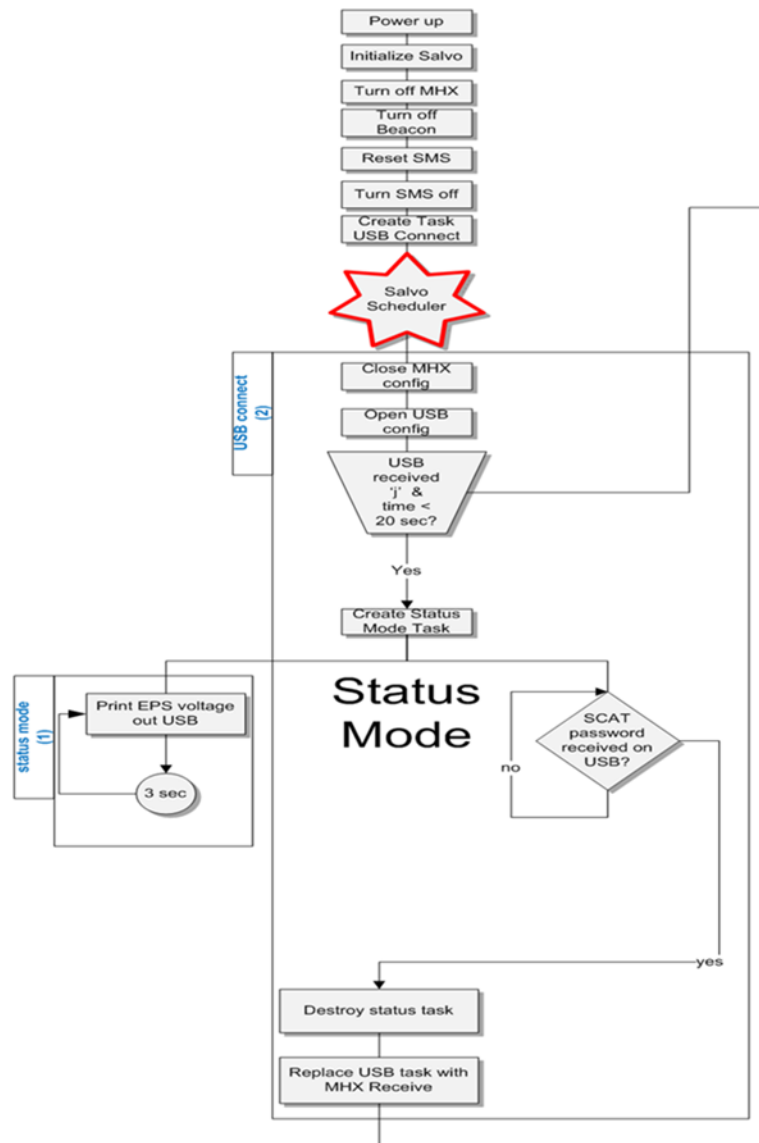


Figure 11. CONOPS start-up into status mode [From 24]

The second mode results after the 20 second wait elapses without the required Status Mode input. This will place the satellite into Flight Mode, turning off the USB interface and opening the MHX interface. Figure 12 shows

the flow path for initiating Flight Mode. The CPU will check the number of resets stored in the non-volatile memory on the spacecraft. If this is the initial reset, signifying the leaving of the launch vehicle, a 30-minute wait will result. The 30-minute wait ensures the spacecraft will not transmit radiation while in the vicinity of the launch vehicle or other spacecraft. After the wait the memory card stores another reset so any subsequent on-orbit restart will not require the 30-minute wait. The Salvo scheduler will create the specific tasks used on orbit and establish multitasking functionality.

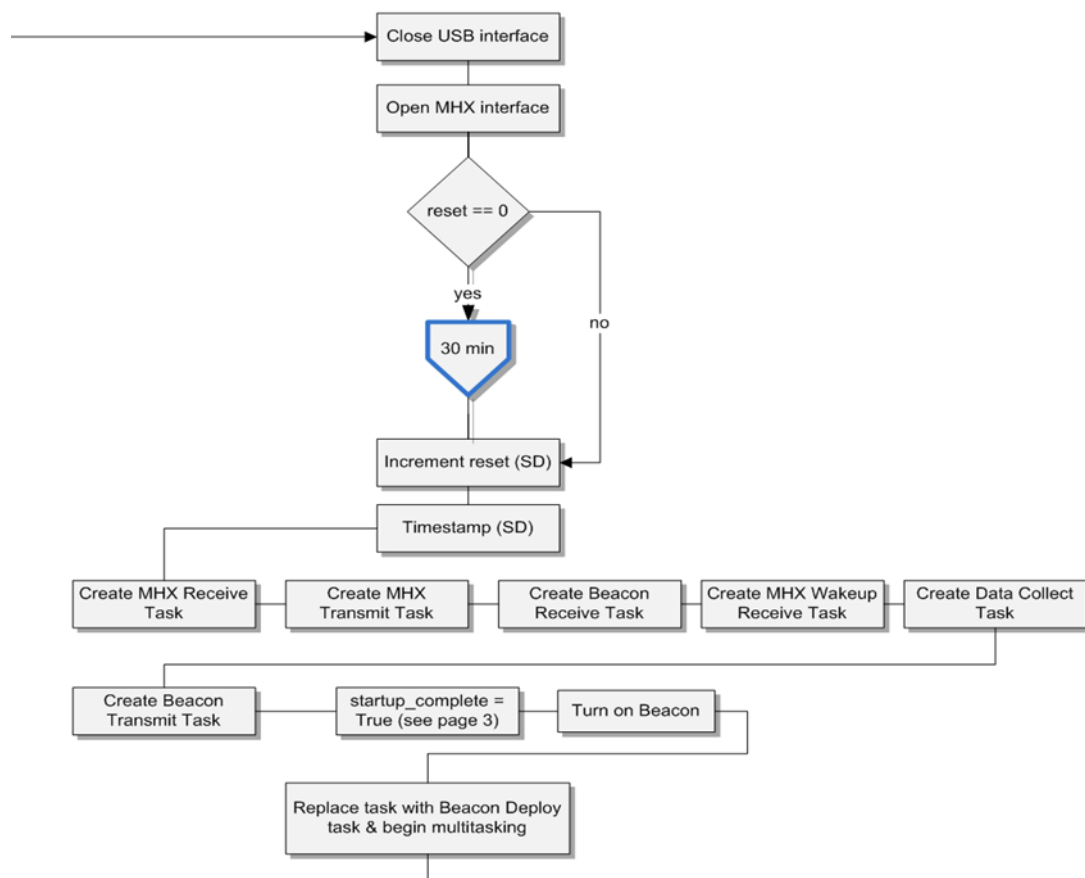


Figure 12. NPS-SCAT flight mode [From 24]

B. OPERATIONS ON ORBIT

The initial task performed by Salvo is to deploy the beacon antenna. Figure 13 shows the flow diagram for beacon deploy. Battery voltage is measured to see whether it exceeds a predetermined value of 7.2V. If not above this threshold, Salvo will delay antenna deployment until the battery voltage is sufficient. If the threshold voltage is met, Salvo will activate the antenna deployment circuitry. Feedback circuitry is built into the +Y face of NPS-SCAT to verify beacon antenna deployment. Switches are connected to the hooks on the +Y for mechanical feedback. If the feedback circuit does not indicate the antenna is deployed, Salvo will attempt to deploy the antenna a maximum of three times. If the antennae is successfully deployed a flag is tripped to allow the beacon board to radiate. If after the third attempt the feedback circuit does not indicate the antenna deployed the Beacon deploy task is ended. This is to protect the circuitry of the beacon board from absorbing the RF energy that is supposed to be radiating out the antennae.

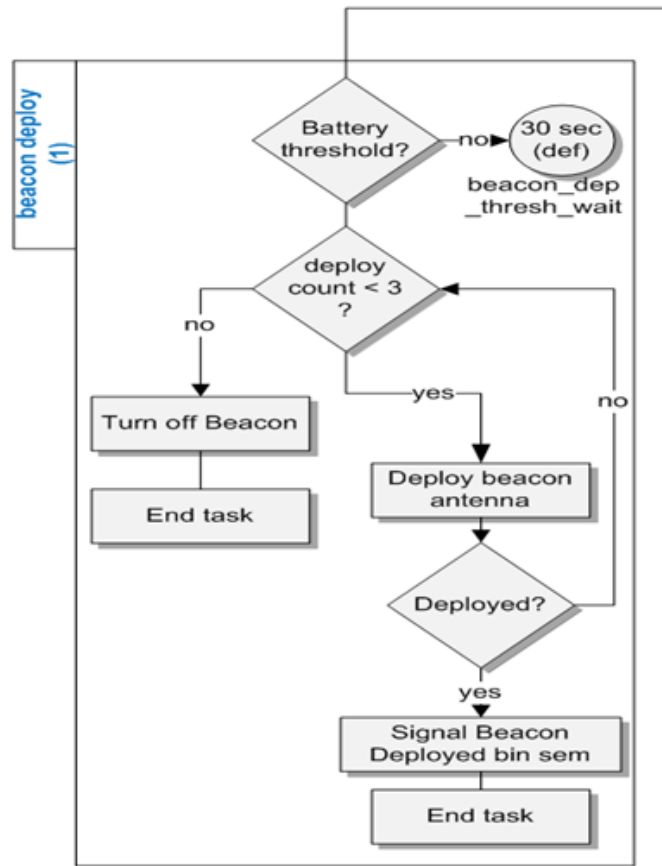


Figure 13. Beacon deploy diagram [From 24]

Interrupt-driven tasks are commands that run when the event that they are waiting on occurs. Two are triggered from ground station commands, while the third is triggered from link-up with the ground station. The two triggered from commands by the ground station are the MHX receive and Beacon receive tasks. Both await receipt of a character. Once in receipt the task will validate the command and if the command is valid the command is executed. The manual interrupts allow the ground station operators to transmit operations to the Satellite. When the MHX radio links up with the ground station, the third Interrupt will automatically send the most recent packet of data collected

on orbit containing IV cures, telemetry, and housekeeping data. Figure 14 shows the flow diagram for the three interrupt driven Tasks.

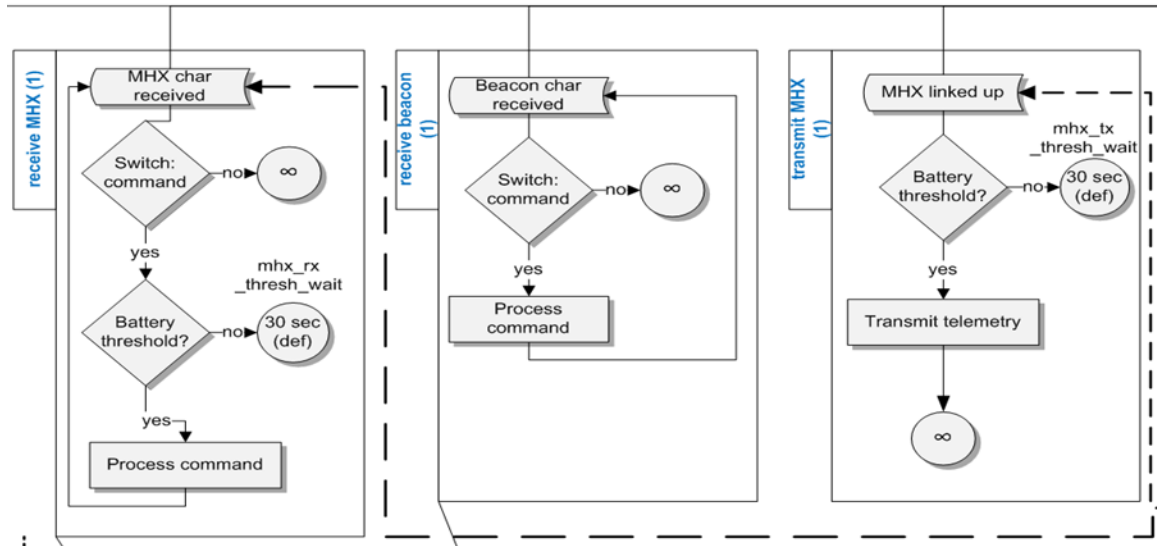


Figure 14. Diagram of interrupt driven tasks [From 24]

The timer driven tasks are just that, they are autonomous actions that take place at determined time intervals after the task is set up. The three time driven tasks are MHX Wakeup, Beacon Transmit, and Data Collect. Figure 15 shows the flow diagram of the three tasks. The MHX Wakeup action turns on the MHX radio until it links with the NPS ground station. The radio will transmit for 15 seconds every 2 minutes until it gets a successful handshake. Once the ground station links with the radio it will transmit for five minutes then stay off for 80 minutes, to allow the satellite to orbit the earth about once before trying communications again. This will help with power management on-orbit since the only ground station that is expected to link up to the S-band MHX radio is at NPS. The Beacon Transmit task will transmit the

latest telemetry data at a five-minute interval. This will be in the amateur radio UHF band so anyone can download the telemetry. The third task is the Data Collect. At a minimum, this action will collect a timestamp, temperature, and EPS state. If the +Z-axis is in the sun, which means that there is no current being generated on the -Z face, the SMS will be turned on and the sun sensor will measure the sun angle for the telemetry data. Once verified in the sun, an I-V curve and timestamp will be collected for each test cell. If the sun sensor cannot measure the sun angle, another timestamp will be taken, and the SMS will be turned off. Data collected will be saved to the SD card with a unique identifier that can be requested by the ground station. This task will repeat every 10 minutes.

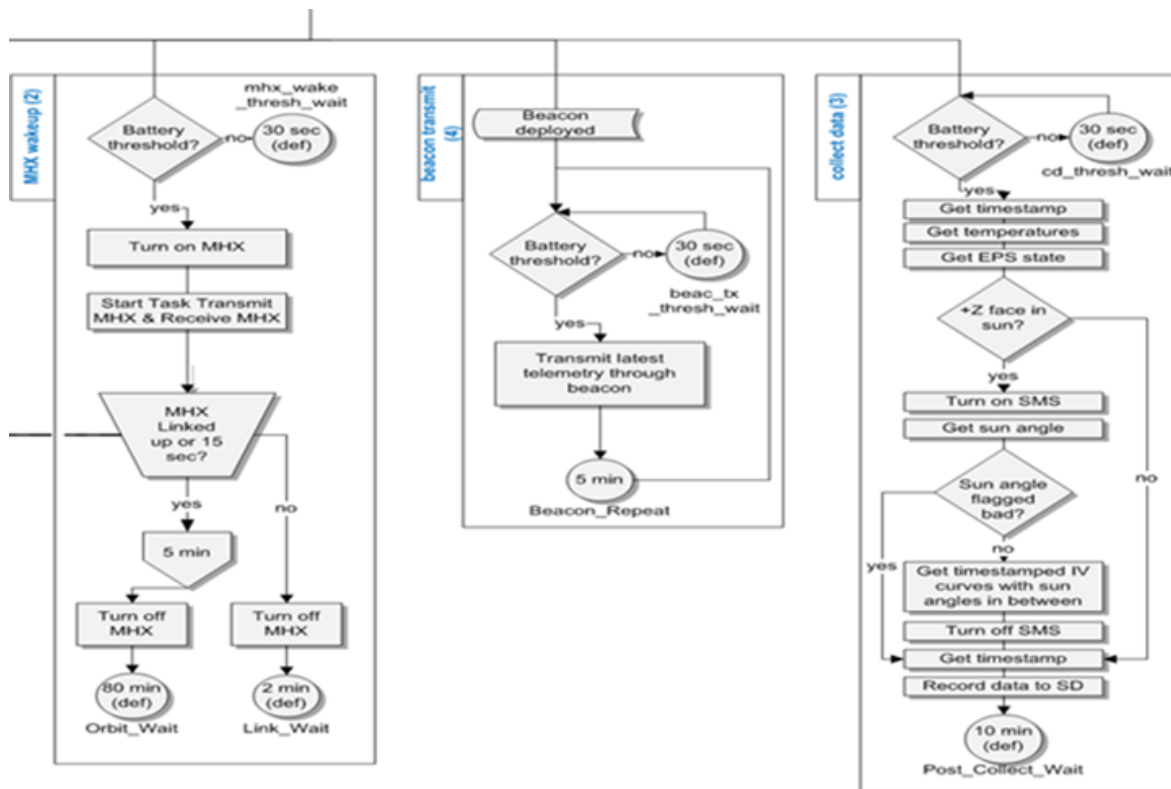


Figure 15. Diagram of timer driven task [From 24]

C. GROUND STATION

NPS's ground segment includes the Mission Operations software, the ground station and associated networks and data base. The Mission Operations software is responsible for satellite pass planning, contingency operations, and data management. The ground station acts as the communications element of the ground segment. The ground station is required to provide daily contact with the spacecraft to allow telemetry housekeeping, data downlink, and command uplink. Ground segment networks and data base include the command links between the ground station and the Mission Operations software, as well as the SSAG Small Satellite Data Base.

1. Mission Operations Software

The Mission Operations Software consists of three operational elements: satellite pass operations, command action implementation, and data management. The satellite pass element adjusts the ground station elements to the anticipated pass in order to close the link between satellite and the NPS ground station. Command operation will contain the communication required to achieve specific tasking, or conduct contingency adjustments such as battery capacity, time changes for check delays, as well as the ability to reprogram the MHX on orbit. The data management activity will synchronize with the Data Base to store the housekeeping telemetry as well as the payload data, in particular the IV curves and associated data, gathered from each orbit.

2. Ground Station

NPS's ground station has antennas that have been setup to communicate with different frequency bands. One antenna is setup in the L and S-Band and others are setup to cover the UHF/VHF bands.

a. MHX2400 Ground Station

The ground station that will be used for the MHX2400 is the antenna covering the L and S-Band. The ground segment includes a 3-meter parabolic dish antenna, which is operated through the mission operation software that sends commands to the rotor controller, adjusting the azimuth and elevation angles of the dish. The mission operations software controls the ground station through an orbit propagator embedded in Northern Lights Software's

Nova program. The mission operations software relays commands through a modem via a frequency synthesizer, which mixes the intermediate frequency with the carrier frequency, back to the modem and then out the antenna. Receiving data back from NPS-SCAT will be completed in a similar reverse order from the antenna to the modem to the mission operations software. There are multiple other inputs to the software, which include a weather station, a video camera that watches the entire ground station, and a GPS [26].

b. Beacon Ground Station

A second set of antennas that will be used for NPS-SCAT's beacon is setup for UHF/VHF communications. In addition to the antenna, the hardware includes a transceiver, a TNC, and a tracking device, all linked to the same mission operations software. NPS-SCAT will operate within the Amateur frequency band of 420-480 MHz. To clear buildings in the vicinity, the antenna tower is roughly ten meters high and includes two circular polarized Yagi-Uda antennas and a discone antenna. The Yagi antennas are designed for circularly polarized radiation, and are capable of receiving any orientation of linear polarized signals. The discone antenna is used to provide a broadband omni-directional antenna that does not require tracking for operations. The TNC consists of a microprocessor, a modem, and software, which provides a command line interface. The TrakBox is a tracking device that can be remotely controlled. The Nova software, which is also used in the MHX2400 ground station, is used to control the direction and elevation the antenna is pointing [26].

3. Ground Network and Data Base

The ground network provides physical links between the mission operations computer and the ground station allowing the linking of the satellite. The campus intranet will be used for the purpose of transferring all data to the Data Base server at NPS.

D. CONTINGENCY OPERATION

1. Power Management Failure

This section describes the autonomous response of NPS-SCAT when the EPS experiences a low power condition. The EPS on NPS-SCAT continuously monitors the battery voltage. Although the CONOPS has been designed to avoid overly depleting the batteries, a low power contingency could occur if the spacecraft has been performing excessive communications in support of normal operations and has not been allowed enough power regeneration time. When the batteries reach a low voltage of 6.2V, the EPS will initiate an automatic disconnect of the 3.3V and 5V conditioned power to prevent further discharge and damage to the batteries. The spacecraft remains powered off to allow the batteries to recharge. The EPS will automatically restore normal power when the battery voltage reaches approximately 7V.

2. Loss of communications

The ground station antennas will steer to and point at the location where the spacecraft is predicted to come over the horizon. During a normal pass, the ground station will send a command to the UHF beacon to turn on the MHX. The ground station would then acquire the MHX signal and use it

to establish a connection with the satellite's S-band transmitter to enable communications. When the S-band cannot be located using standard methods the ground station operators will verify that the ground station is operational and is not at fault for the lack of acquisition. The ground station will transmit a command to the spacecraft to activate the S-band transmitter and high gain antenna and commence downlink of telemetry data. The S-Band radio and patch antenna are expected to be the primary means of data downlink, at 9.6 kbaud, from NPS-SCAT. Should the S-band system fail, the spacecraft may be commanded through the Cal Poly beacon to downlink its telemetry using the beacon, though at a lower data rate, 1.2 kbaud. During this scenario, the ground station will lock onto the satellite using the beacon and then upload commands and download data using the UHF-band radio. A command will be sent to the beacon radio to get the MHX's status and correct its configuration, if necessary.

Should the ground station not be able to acquire the beacon signal using the standard search strategy, then, if the S-band has been established, the ground station will transmit a command to the spacecraft via the S-band transmitter and attempt to establish the status of the Beacon.

3. Failed beacon antenna deployment

This describes the response if the NPS-SCAT beacon antenna does not deploy properly during the initial deployment. After the three tries coded into the software the deploy action will not be automatically attempted again. However, the ground station can send the command

action to NPS-SCAT enabling the deployment mechanism to retry. If this is unsuccessful there are no further actions that can be attempted. At the altitude of 350 km the fishing line holding the antennae will most likely not degrade from UV or atomic oxygen in a short period of time. An orbital lifetime of six months or so might be long enough to degrade the fishing line and result in a deployment of the beacon antenna.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. ORBITAL ENVIRONMENT

A. SPACE ENVIRONMENT

NPS-SCAT will be inserted into low-earth orbit. The initial orbit is set to be at just below the Space Station altitude of about 350 km and inclination of 51.6°. The natural environment at this orbit includes the gravitational field, atmospheric plasmas, magnetic fields, energetically charged particles, galactic cosmic rays, meteoroids, as well as additional concern of manmade orbital debris. Each concern will be covered briefly with a more in-depth discussion reserved for the radiation environment and its effects presented later in this chapter.

1. Plasma

Spacecraft in low orbit around the earth have a complex interaction with ionospheric plasma due to both the solar wind and the geomagnetic tail. NPS-SCAT will be placed within this dynamic plasma environment risking damage from spacecraft charging, and interference with communication and other electronic hardware due to scintillation and wave refraction. The LEO plasma environment is at lower energy and higher density. The electron/ion density is about 10^2 - 10^6 cm³, the electron impact energy is about 0.3eV, and the ion impact is 5eV. LEO plasma density is approximately equally distributed between electrons and ions [21]. Differential collection of charge on the external surfaces of the spacecraft may lead

to electrostatic discharge events and attraction of contaminants. Severe charging can also interfere with electronic systems.

2. Orbital Debris and Meteoroids

Orbital debris will be a concern for the spacecraft. Space debris has become a greater risk for low orbit missions in recent years. Micrometeoroids exist naturally in the solar system from breakups of comets and asteroids, but the numbers of these are small and they don't typically orbit earth. Space debris, however, is becoming a greater concern to spacecraft due to the increased frequency of space flights. This debris includes leftover satellites, broken-up rocket stages and even paint flakes from deteriorating spacecraft. There are currently over 20,000-catalogued objects greater than five centimeters in diameter in the low earth orbit environment. Smaller objects probably number in the hundreds of thousands [27].

The consequences of a collision between NPS-SCAT and a micrometeoroid or a piece of space debris could be catastrophic to the spacecraft. Collisions take place at hyper-velocities of up to ~15 km/s with dissipation of large kinetic energies for even very small particles. While estimating the likelihood of space debris impacting NPS-SCAT is beyond the scope of this thesis, to help predict the likelihood of damaging meteorite impacts STK's SEET (Space Environment & Effects Tool) was used for analysis. As you can see in Figure 16 the probability of impact at 350km is relatively small, at most 4.3×10^{-10} per day with an expected mass of meteoroids between .001 and 1 gram. The

extremely low probability, coupled with the short amount of time in orbit at that altitude, means that there is virtually no chance of a significant impact during the mission.

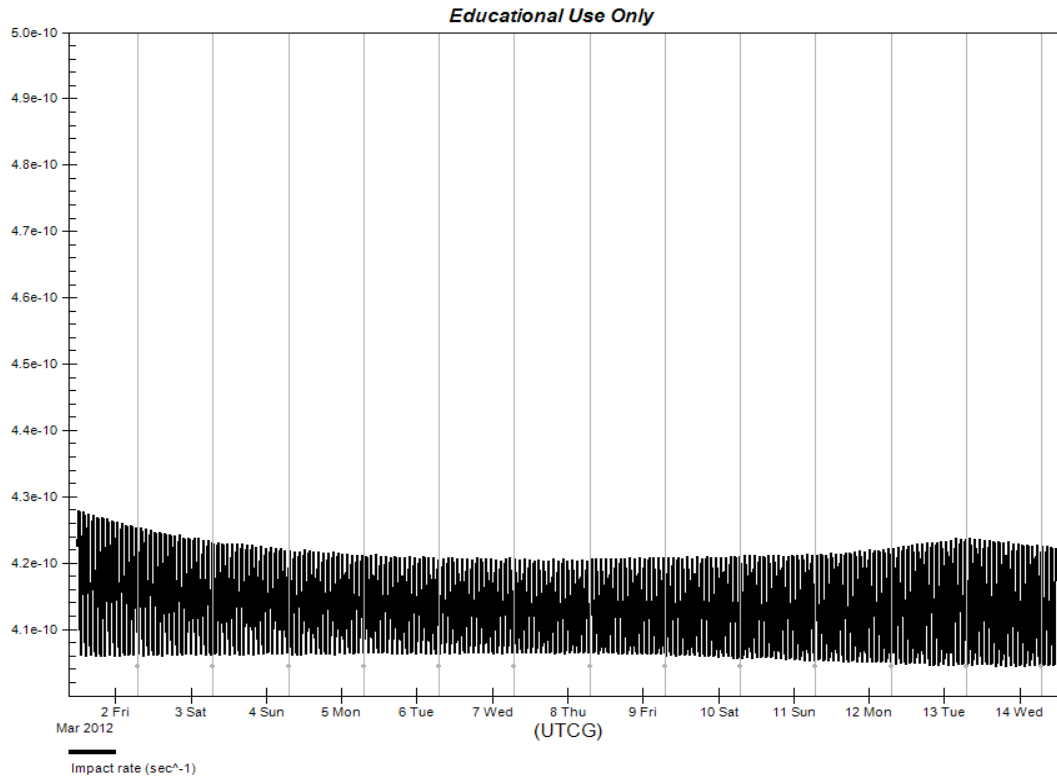


Figure 16. Probability of partial impact at 350 km.

Figure 17 shows the probability of impact at 500 km which is also quite small, at less than 1.8×10^{-10} per day.

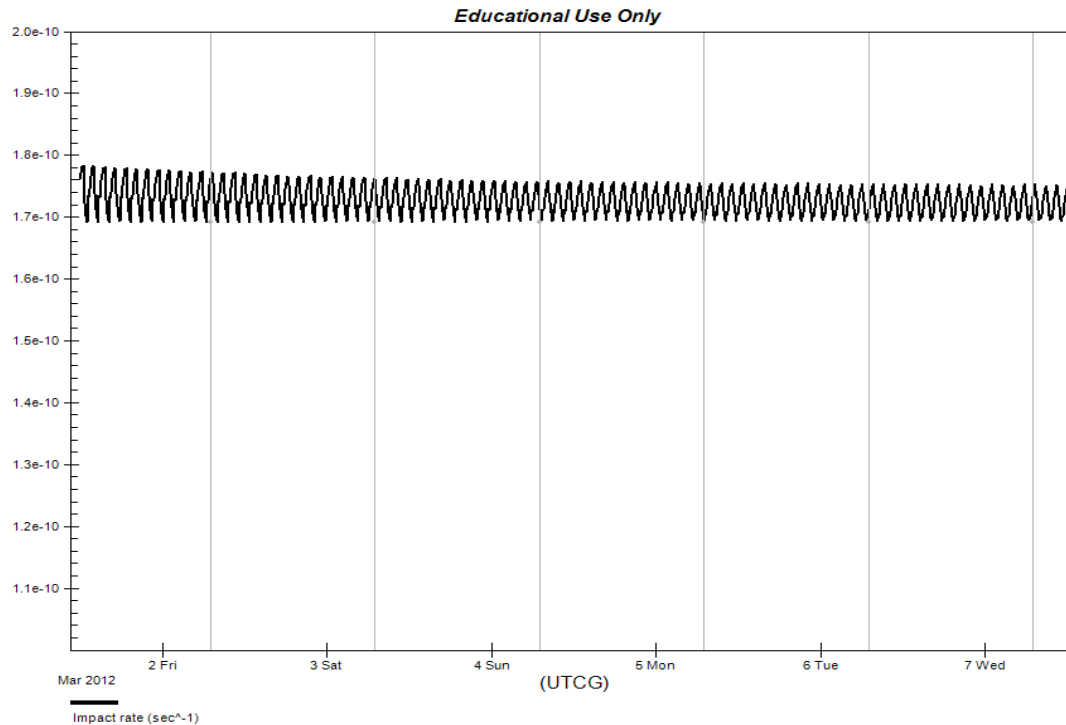


Figure 17. Probability of partial impact at 500 km.

3. Surface Degradation Hazards

Atomic oxygen in low-Earth orbit is highly reactive and erodes the external surfaces on satellites. Atomic oxygen is very damaging to solar cells, as well as to polymers such as the fishing line holding the antennas and the antenna corner protector. UV degradation may occur as well due to the presence of ultraviolet and X-ray wavelengths. This was originally a contingency design for the beacon antenna deployment system. Failure to deploy would result in the degradation of the fishing line securing the antenna, eventually causing the line to fail

and allowing the antenna to deploy. This benefit most likely will not be realized during the initial flight due to the limited time frame of exposure.

4. Perturbations

The Earth-Moon system will cause perturbations within NPS-SCAT's orbit caused by the eccentricity between the Earth-Moon orbit and the rotation of the Earth and Moon. The planets will also perturb the orbit, with Jupiter and Venus acting as the primary disturbance sources. Additional sources of perturbation include solar radiation pressure and atmospheric drag. These perturbations will vary due to attitude changes of the spacecraft. Atmospheric drag is the primary factor affecting orbital lifetime.

5. Orbital decay

Orbital lifetime in LEO is largely affected by atmospheric drag. Orbital decay thus involves a positive feedback effect, where the more the orbit decays, the lower its altitude drops, and the lower the altitude, the faster the decay. Atmospheric decay is also sensitive to external factors of the space environment such as solar activity, which heats the atmosphere and expands its influence. Figure 18 shows the graph of NPS-SCAT's orbital lifetime versus altitude. The orbital range of 400-500 km is the range that would meet NPS-SCAT's desired lifetime. An orbit of 600 km or greater would result in a lifetime greater than 25 years and exceed the maximum allowable time before reentry. As mentioned, the first flight of NPS-SCAT will be at about 350 km altitude and such an orbit will allow NPS-SCAT to remain in orbit around 64 days. This calculation is

an estimate and is used for the subsequent radiation exposure analysis. Default values for coefficients representing the satellite characteristics are considered conservative as these values are set for the maximum drag. Average drag area for the satellite was estimated to be $.0125 \text{ m}^2$ at a mass of 1.1 kg.

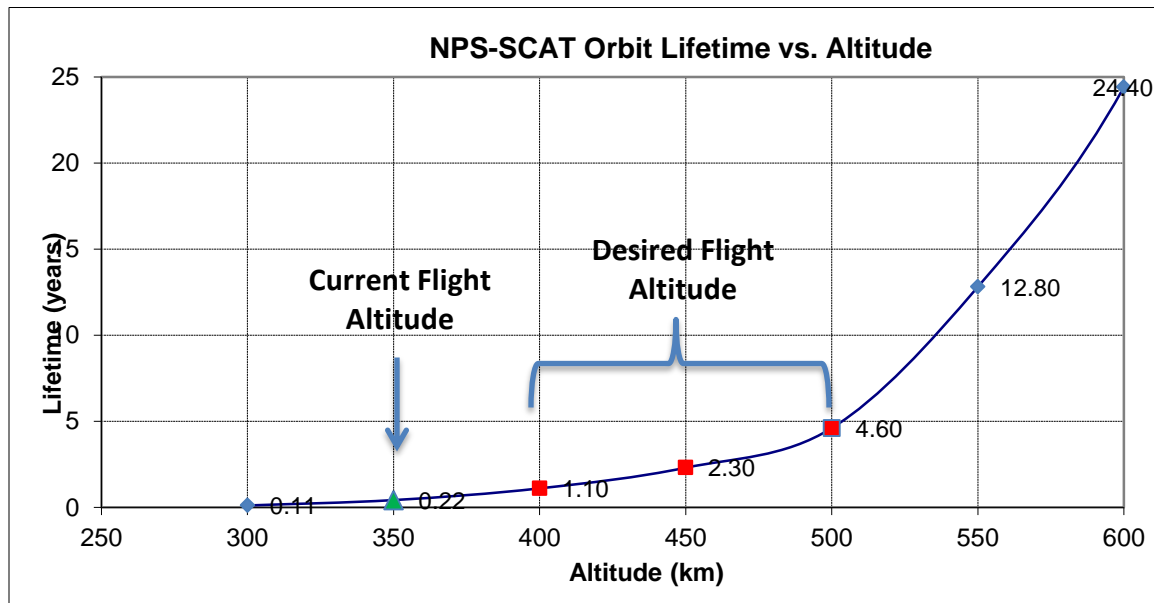


Figure 18. NPS-SCAT's Orbit lifetime estimate as a function of altitude.[After 22]

6. Energetic Particles

NPS-SCAT will be subject to the effects of energetic particles, or ionizing radiation, produced by solar flares and coronal mass ejections, the geomagnetic tail, and galactic cosmic rays. The spacecraft in the initial orbit will be slightly under the South Atlantic Anomaly but our desired orbit of around 500 km would encounter ionizing radiation trapped in the Van Allen belts and in particular the South Atlantic Anomaly. This ionizing radiation can

cause several types of damage. These effects include measurable changes in properties of semiconductors and a deterioration of the thermal radiation properties of materials due to the cumulative penetration of the particles. The energetic particles can also cause single event upsets (SEUs) to microcontrollers and changes in the surface reflectivity and transmission properties of optical sensors. Energetic particles will also add noise to images due to direct impacts with the sensor. This effect will be more pronounced during periods of high solar activity.

B. RADIATION ENVIRONMENT

At an orbital altitude of 350 km, NPS-SCAT will be within the earth's magnetosphere. This results in exposure to higher fluxes of ionizing radiation. The primary radiation sources are galactic cosmic rays that are energetic particles from outside our solar system, particles trapped in the earth's magnetic field known as the Van Allen Belts, and solar flares. High-energy protons and heavy ions emanate from the Sun and elsewhere in the cosmos.

1. Solar Cell

Specification sheets for three out of four solar cells used on the spacecraft contain the degradation information that will be used for analysis. The corresponding Tables show the expected degradation for each cell, with the exception of the polycrystalline silicon cells, used primarily for terrestrial use, for which there is no representative data for comparison. Degradation is listed as a percentage from baseline. Three parameters will be

reviewed for solar efficiency. Those three parameters are short circuit current (I_{SC}), open circuit voltage (V_{OC}), and max power (P_{MAX}). Tables 5-7 show the data sheet input for degradation of the solar cells.

| Spectrolab 26.8% Improved Triple Junction (ITJ) Solar Cells | | | |
|--|--------------------------|--------------------------|--------------------------|
| Radiation Degradation | | | |
| (Fluence 1MeV Electrons/cm²) | | | |
| Parameters | 1x10¹⁴ | 5x10¹⁴ | 1x10¹⁵ |
| Imp/Imp0 | 1 | 0.98 | 0.96 |
| Vmp/Vmp0 | 0.94 | 0.9 | 0.88 |
| Pmp/Pmp0 | 0.94 | 0.88 | 0.84 |

Table 5. Test Cell 1, ITJ [From 17]

| EMCORE. "28.0% Triple Junction with Monolithic Diode (BTMJ) | | | |
|--|--------------------------|--------------------------|--------------------------|
| Radiation Degradation | | | |
| (Fluence 1MeV Electrons/cm²) | | | |
| Parameters | 1x10¹⁴ | 5x10¹⁴ | 1x10¹⁵ |
| Imp/Imp0 | 1 | 0.96 | 0.94 |
| Vmp/Vmp0 | 0.96 | 0.92 | 0.9 |
| Pmp/Pmp0 | 0.96 | 0.89 | 0.85 |

Table 6. Test Cell 2[From 18]

| Spectrolab 28.3% Ultra Triple Junction (UTJ) Solar Cells | | | |
|---|--------------------------|--------------------------|--------------------------|
| Radiation Degradation | | | |
| (Fluence 1MeV Electrons/cm²) | | | |
| Parameters | 1x10¹⁴ | 5x10¹⁴ | 1x10¹⁵ |
| Imp/Imp0 | 0.99 | 0.98 | 0.96 |
| Vmp/Vmp0 | 0.94 | 0.91 | 0.89 |
| Pmp/Pmp0 | 0.93 | 0.89 | 0.86 |

Table 7. Test Cell 4[From 20]

AGI's STK and NASA's Solar Cell Radiation Handbook were used as tools to help predict the total dose from the radiation environment to evaluate the degradation of the test solar cells. There are other tools available but these are the two used for this analysis.

2. STK/SEET

AGI's STK SEET module was the first software that was used to model the projected radiation exposure. The radiation usually of interest in the study of degradation of materials and devices consists of energetic, massive fast particles. Results from such an analysis help enable calculations of solar cell efficiency degradation due to the space environment. Calculations were based on the following inputs: 350km altitude, 50-degree inclination, spherical silicone detector, shield thickness 50 mils aluminum, and the static value representing a 15-day average geomagnetic activity index. The characteristics were implemented into the NASA calculation model. The minimum thickness allowed to be selected is 50mils or 0.0127mm. NPS-SCAT does not have 50 mils of Al shielding or an equivalent. Future analysis is required to determine the equivalent thickness of NPS-SCAT and incorporate that thickness into a model that can be analyzed for specific radiation effects. Table 8 shows the results for one month on orbit. The calculation takes three to five hours per run due to the system adding up the total flux from electrons and protons.

| Shielding thickness (Mils) | Combined dose (rads) |
|----------------------------|----------------------|
| ----- | ----- |
| 50 | 377.7 |

Table 8. Combined total dose in rads at 350km and 50 mils shielding for one month.

Figures 19 and 20 show the various fluxes anticipated for a specific day on orbit. Figure 19 represents the anticipated flux based of electron interaction and Figure 20 depicts the flux from proton interaction. The same characteristics were used to compute the output for the total dose. The figure show three different energy flux levels throughout the orbit and the peaks coincide with the satellite's passage through the South Atlantic Anomaly.

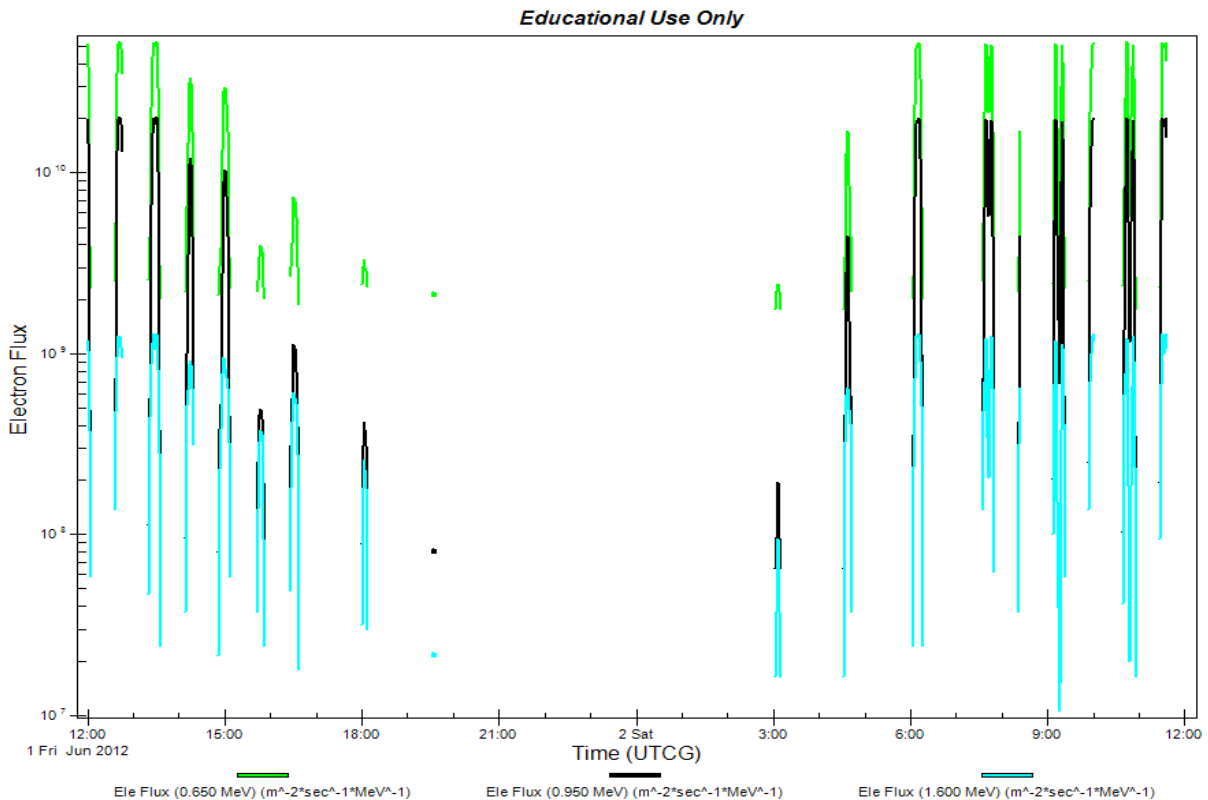


Figure 19. STK "NASA electron flux" for a day

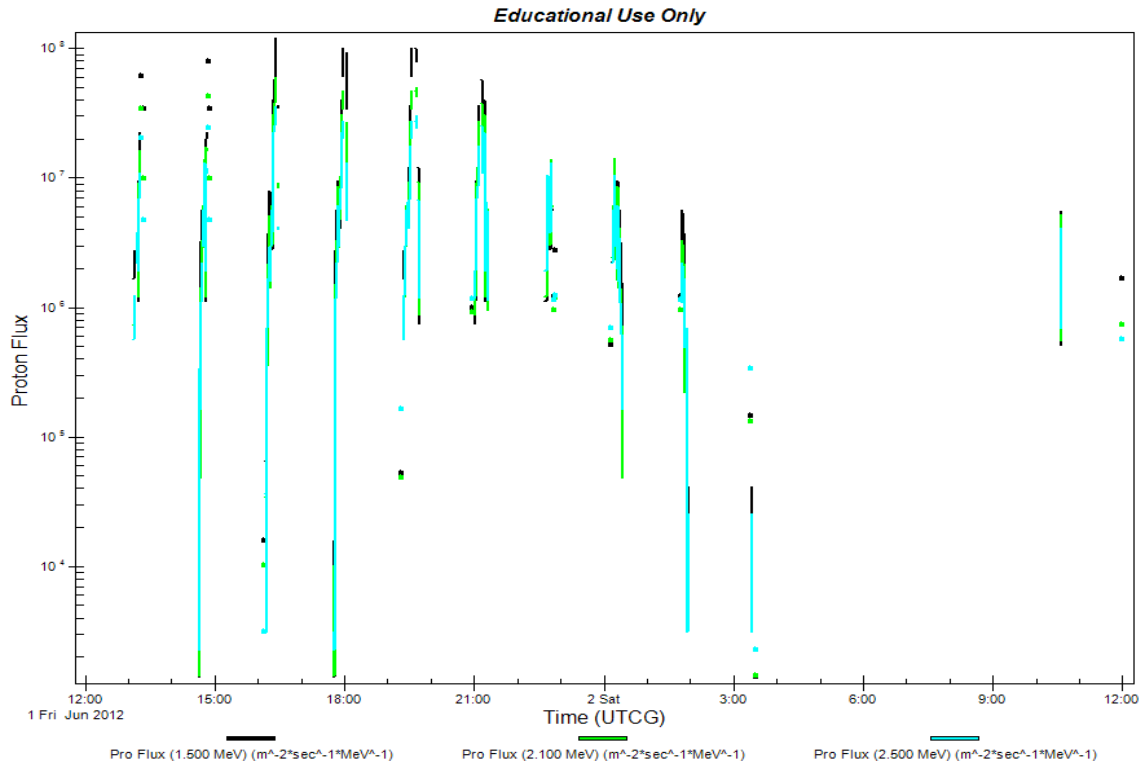


Figure 20. STK "NASA proton flux" for a day

3. NASA Solar Cell Radiation Handbook

The handbook [25] is used to predict the degradation of solar cells and their electrical performance in any given space radiation environment. The estimates are quoted as the interaction of energetic charged particles represented by a one MeV equivalent electron fluence for a year's orbit. The Tables within the book were generated using a computer program written by NASA to calculate the equivalent fluence, with calculations at various altitudes and shield thicknesses. Data detailing the radiation fluence levels for specific effects by different particles was calculated as a function of one MeV electron fluence. At first a linear interpolation was used to obtain table values for our reference orbit, but it was discovered that

a polynomial was a better fit for the data. Table 9 shows the calculated values for 50 mils of Aluminum shielding that was used for comparison with STK's SEET values. For each altitude the values just below and above where selected to approximate the Fluence at 50 mils. The e^{power} is a representation of exponential value at that specific altitude. The interpolation column is for comparison of the values from the book with the values calculated at each mils thickness, as well as the desired 50 mils thickness.

| Electrons | | | | Protons | | | |
|-----------|------|----------|---------------|---------|------|----------|---------------|
| Alt-Km | mils | book | interpolation | Alt-Km | mils | book | interpolation |
| | | e^{10} | | | | e^{10} | |
| 277 | 12 | 4.59 | 4.56 | 277 | 12 | 19 | 18.63 |
| | 20 | 3.59 | 3.65 | | 20 | 13.8 | 14.60 |
| | 30 | 2.77 | 2.73 | | 30 | 11.4 | 10.92 |
| | 60 | 1.44 | 1.44 | | 60 | 8.89 | 8.93 |
| | 50 | | 1.63 | | 50 | | 8.09 |
| | | e^{11} | | | | e^{11} | |
| 463 | 12 | 9.36 | 9.29 | 463 | 12 | 15.2 | 14.79 |
| | 20 | 7.18 | 7.33 | | 20 | 10.5 | 11.39 |
| | 30 | 5.47 | 5.38 | | 30 | 8.42 | 7.89 |
| | 60 | 2.79 | 2.80 | | 60 | 2.27 | 2.32 |
| | 50 | | 3.11 | | 50 | | 3.35 |
| | | e^{12} | | | | e^{12} | |
| 555 | 12 | 12.70 | 12.60 | 555 | 12 | 3.25 | 3.17 |
| | 20 | 9.66 | 9.88 | | 20 | 2.22 | 2.39 |
| | 30 | 7.31 | 7.18 | | 30 | 1.77 | 1.67 |
| | 60 | 3.69 | 3.70 | | 60 | 1.31 | 1.32 |
| | 50 | | 4.09 | | 50 | | 1.14 |
| | | e^{12} | | | | e^{12} | |
| 833 | 12 | 26.4 | 26.12 | 833 | 12 | 15 | 14.63 |
| | 20 | 19.3 | 19.91 | | 20 | 9.99 | 10.79 |
| | 30 | 14.2 | 13.84 | | 30 | 7.77 | 7.30 |
| | 60 | 6.92 | 6.95 | | 60 | 5.51 | 5.55 |
| | 50 | | 7.36 | | 50 | | 4.68 |

Table 9. Calculated Fluence for 50 mils for electrons and protons for desired Altitudes at various shielding thicknesses.

A polynomial approximation was calculated from the handbook numbers by graphing four shielding values, three lower and one higher than the desired 50 mil reading, with the associated electron fluences for each altitude. A polynomial trend line was then selected. Once an approximation for shielding was calculated an additional approximation was calculated by graphing altitude with the electron fluences. This approximation was then used to calculate the expected dose at 350 km and 50-degree inclination in Table 10. An additional interpolation was conducted for 500 km to represent desired Flight 2 parameters, also shown in Table 11.

| Test Cell Analysis | ISC | VOC | PMAX |
|----------------------------|----------|----------|----------|
| 350 km 50 degree | 1.86E+12 | 2.87E+13 | 2.87E+13 |
| Test Cell 1 Spectrolab ITJ | 1 | 1 | 1 |
| Test Cell 2 EMCORE BTMJ | 1 | 0.97 | 0.97 |
| Test Cell 4 Spectrolab UTJ | 1 | 1 | 1 |

Table 10. Solar Cell Radiation Handbook Calculations for Total Dose with Test Cell Analysis of percentage remaining at 350km 50degree[After 25].

4. South Atlantic Anomaly

A portion of the SEET module computes South Atlantic Anomaly transit times and probable fluxes within an orbit. This could be used to help mitigate the risk of SEUs. By estimating expected South Atlantic Anomaly entrance and exit times, it is possible to determine when to turn off or reboot a LEO spacecraft, if it were particularly sensitive to SEUs. The 51.6-degree orbital inclination of NPS-SCAT will cause it to pass through the South Atlantic Anomaly daily. This region, located east of Argentina, is characterized by irregularities in the earth's geomagnetic

field causing trapped energetic particles at lower altitudes. Unfortunately, the analysis portion of this module only evaluates for 400km altitude and above so it was not useful for NPS-SCAT's Flight 1 parameters. It could be used on Flight 2 mission if we are able to get within the desired orbit of 400-500km.

C. FUTURE WORK FOR NPS-SCAT

1. Finalize Flight Software

The CONOPS has been established and reviewed with software engineers to maintain open dialog between software and hardware engineers. Software coding continues in order to achieve the desired level of functionality and robustness. Testing the software while installed in the fully integrated satellite is continually conducted as new code is written to insure full functionality of the satellite in accordance with NPS-SCAT CONOPS.

2. Final Flight Integration

Flight Unit 1 has been conformal coated and placed in storage awaiting final integration and software. This must be completed sometime before June 2012, the date for delivery for flight integration.

Flight unit two is also complete and in storage. Unit 2 does need to be conformal coated prior to integration. It will be available for future flight opportunities.

3. Launch and Operations

The ground system still needs to be developed to manage communications with the spacecraft, data management functions, and flight operations. Details need to be worked

out on how data collected from amateur radio operators will get back to NPS. This is where future personnel involvement is most needed. The on-orbit data will need to be organized and analyzed, and results recorded.

D. SUMMARY

The program management and systems engineering challenges and lessons learned have been outlined through multiple theses and should be a useful guide for future CubeSat projects at the Naval Postgraduate School. Milestones have been maintained and met via established documents. Cost, performance, schedule and risks must all be equally monitored continuously throughout the project. NPS-SCAT has been an excellent way to exercise project management in an environment that fosters learning.

E. CONCLUSION

The expected dose for NPS-SCAT at 350km and 500km is listed in Table 11. Negligible degradation is expected for the 350km orbit, as the orbital lifetime is expected to be only one or two months. The radiation dose values were based on a year on orbit, and NPS-SCAT Flight 1 has an expected lifetime of 30-60 days. If it were on orbit for a year the numbers fall below the test cells documented data sheets and should have no appreciable effect on the various solar cells. Although this reduces the significance of NPS-SCAT's experimental goal even if it gets a one-year flight, NPS-SCAT will still be able to validate the ability to take and deliver data from the cells on orbit proving its utility as a solar cell array tester. Ideally we would like to get a flight for the second NPS-SCAT Flight Unit at an

orbit of about 500km. At this altitude we could start to see degradation and record the results. Table 11 shows the anticipated degradation for the cells based on five years on-orbit at that altitude.

| Test Cell Analysis | ISC (MeV) | VOC (MeV) | PMAX (MeV) |
|----------------------------|-----------|-----------|------------|
| 500 km 50 degree | 1.59E+13 | 1.08E+14 | 1.08E+14 |
| 5 YEAR | 7.95E+13 | 5.40E+14 | 5.40E+14 |
| Test Cell 1 Spectrolab ITJ | 1 | 0.9 | 0.88 |
| Test Cell 2 EMCORE BTMJ | 0.97 | 0.92 | 0.89 |
| Test Cell 4 Spectrolab UTJ | 1 | 0.91 | 0.89 |

Table 11. Test Cell Analysis of percentage remaining at 500km 50degree for five years.

LIST OF REFERENCES

- [1] NASA, "Education at Kennedy, inspire engage educate employ," February 2011,
http://www.nasa.gov/offices/education/centers/kennedy/technology/elana_feature.html.
- [2] D. A. Bearden, "Aerospace Small Satellite cost model," 14 May 2007,
<http://www.aero.org/publications/crosslink/winter2001/04.html>.
- [3] B. Obama, "National Space Policy of the United States of America," June 2010,
http://www.espi.or.at/images/stories/dokumente/diverse/national_space_policy_6-28-10.pdf
- [4] K. Smith, "Naval Postgraduate School Solar Cell Array Tester," M.S. Thesis, Naval Postgraduate School, Monterey, CA, December 2010.
- [5] A.L. Bein, "NPS-SCAT (Solar Cell Array Tester), The Construction of NPS' First Prototype CubeSat," M.S. Thesis, Naval Postgraduate School, Monterey, CA, September 2008.
- [6] C.S. Malone, "NPS Solar Cell Array Tester: A Program Management Analysis," M.S. Thesis, Naval Postgraduate School, Monterey, CA, September 2009.
- [7] R.D. Jenkins IV, "Master's Student, NPS-SCAT CAD Model," Naval Postgraduate School, Monterey, CA, 2010.
- [8] Texas Instruments, "MSP430F161x family of microcontrollers" August 2011,
http://www.ti.com/lscds/ti/microcontroller/16-bit_msp430/overview.page
- [9] Clyde Space Ltd., CubeSat Power System User Manual: Issue F, Clyde Space Ltd., 2008.
- [10] CubeSat "History & Performance of Pumpkin's Products in Space," August 2010.
<http://www.cubesatkit.com/content/space.html>.

- [11] Microhard Systems Inc., MHX-2400 Operating Manual: 2.4GHz Spread Spectrum OEM Transceiver Revision 1.56, Microhard Systems Inc., 2006.
- [12] C.K. Mortensen, "NPS-SCAT; CubeSat Communications System Design," M.S. Thesis, Naval Postgraduate School, Monterey, CA, September 2010.
- [13] Clyde Space, "1U CubeSat EPS," July 2010, http://www.clyde-space.com/cubesat_shop/eps/8_1u-cubesat-eps.
- [14] L.T. Dorn Jr, "NPS-SCAT: Electrical Power System," M.S. Thesis, Naval Postgraduate School, Monterey, CA, September 2009.
- [15] J. Fletcher, "Electrical Power Subsystem Integration and Test For The NPS Solar Cell Array Tester CubeSat," M.S. Thesis, Naval Postgraduate School, Monterey, CA, December 2010.
- [16] B. Tubb, "1U CubeSat Beacon version 4" California Polytechnic University, San Luis Obispo, CA, April 2008.
- [17] Spectrolab Inc., "26.8% Improved Triple Junction (ITJ) Solar Cells," April 2008, <http://www.spectrolab.com/DataSheets/TNJCell/tnj.pdf>.
- [18] EMCORE. "28.0% Triple Junction with Monolithic Diode (BTMJ) High Efficiency Solar Cells for Space Applications." May 2007, http://www.emcore.com/assets/photovoltaic/Emcore+BTMJ+Cell+Data+Sheet_May-07.pdf.
- [19] The Electronic Goldmine, "Electronic Goldmine, Electric Component, Parts, Test Equipment, Kits," August 2011, <http://www.goldmine-elec.com/solar>.
- [20] Spectrolab Inc., "28.3% Ultra Triple Junction (UJT) Solar Cell," April 2008, <http://www.spectrolab.com/DataSheets/TNJCell/utj3.pdf>.

- [21] L. Wang, X. Qing, Y. Liu. "Anomaly Attributed to Low Earth orbit Plasma Environment," 2001,
<http://www.dev.spis.org/projects/.../78ce5f07c0a80014009069a0f816fabf>.
- [22] R.D. Jenkins IV, "NPS-SCAT: Systems Engineering and Payload Subsystem Design, Integration, and Testing of NPS' First CubeSat," M.S. Thesis, Naval Postgraduate School, Monterey, CA, June 2010.
- [23] P. Reinhardt, "NPS-SCAT CONOPS Explanatory Document," Naval Postgraduate School, Monterey, CA, August 2010.
- [24] A. Felt, "NPS-SCAT Concept of Operation Diagram," Naval Postgraduate School, Monterey, CA, August 2011.
- [25] Y. Tada, J. R. Carter, Jr., B. E. Anspaugh, "Solar Array Degradation" in Solar Cell Radiation Handbook, Third Edition, Pasadena: NASA, 1982, Ch6 pp. 34-37.
- [26] M. P. Schroer, "NPS-SCAT; A CubeSat Communications System Design, Test, and Integration" M.S. Thesis, Naval Postgraduate School, Monterey, CA, June 2009.
- [27] M. Smith, "Space Debris in LEO Continues to Increase," June 2011,
http://spacepolicyonline.com/pages/index.php?option=com_content&view=article&id=1646:space-debris-in-leo-continues-to-increase&catid=75:news&Itemid=68
- [28] K. Smith, "NPS-SCAT Systems Engineering and Test Program," M.S. Thesis, Naval Postgraduate School, Monterey CA, December 2010

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
Ft. Belvoir, Virginia
2. Dudley Knox Library
Naval Postgraduate School
Monterey, California
3. James H. Newman
Naval Postgraduate School
Monterey, CA